An Assessment of the United States Measurement System:

Addressing Measurement Barriers to Accelerate Innovation

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NIST
National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce

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"To measure is to know."† And knowledge – whether aimed at unraveling a fundamental law of nature or ensuring that a manufactured part will fit into its assembly – is critical to continued technical progress, to innovation, and ultimately to the economic security of our nation.

The requirement to measure things more accurately, faster, and at smaller dimensions is now pervasive throughout U.S. science and industry. Whether designing complex nanostructures, exploiting fundamental quantum properties of matter, or probing the chemical pathways inside a cell – the demand for more and better measurements is unrelenting.

Progress to date has been phenomenal. We can now measure time with an accuracy of better than 1 second in 60 million years, measure force to a nanonewton (roughly equal to the force required to sever a single chemical bond between two atoms), and count single electrons and photons.

But as the magnitude and quality of global competition has increased, there is a greater urgency in ensuring that the measurement capabilities required by science and industry are addressed or are in development.

This report documents the breadth of the U.S. Measurement System (USMS). It also documents current unmet measurement needs that pose immediate barriers to technological innovation across a number of industry and technology sectors.

The measurement needs identified in this initial assessment are compelling evidence that new or improved measurement capabilities are required. Meeting this requirement is necessary if we are to continue "*to generate and harness the latest in scientific and technological developments and to apply these developments to real world applications*," as called for in President Bush's American Competitiveness Initiative.

This report should be viewed as a beginning, not as an end product. At NIST, we will use this assessment as a means to focus our own work in support of U.S. innovation and competitiveness. We also will partner with other stakeholders in both the public and private sectors to focus organizational, sectoral, and cross-sectoral attention on overcoming the most significant measurement-related barriers to innovation.

I want to extend my sincere thanks to the hundreds of participants from industry, universities, and government who contributed to the development and authentication of these measurement needs. Your contributions were invaluable.

Ensuring that the nation's measurement infrastructure is robust and forward-looking is a job for all of us. Your continued participation is important as we establish and implement a shared measurement innovation agenda.

William Jeffrey

William Jeffrey
Director

†William Thomson (Lord Kelvin) 1824-1907

NIST

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Appendices

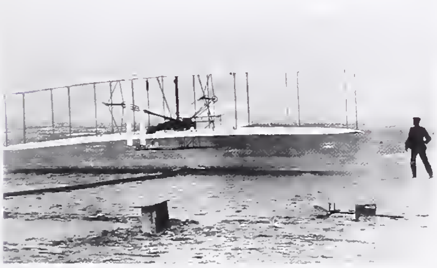
All Appendices are contained on the accompanying CD, along with an electronic copy of this document.

Guidelines for users on searching and navigating the appendices are included in the main directory of the CD.

Foreword

The creation of the Wright Flyer of 1903, the world's first airplane, is a story of *a measurement barrier to technological innovation* overcome.

The Wright Brothers had been vexed by the under-performance of a wing they had designed based on data published by Otto Lilienthal, the foremost glider expert of the day. The lift generated by the wing was but one-third of that expected, and, to their consternation, they were forced to conclude that the measurement data were wrong.



To solve the problem of the inaccurate measurement data impeding their innovation, they built a balance for the precise measurement of the aerodynamic lift of wings of different profiles. Based on the accurate measurement data they produced, they designed the wings and propeller of what came to be recognized as the world's first powered, controlled, heavier-than-air flying machine.

This report is about measurement barriers to potential technological innovations that are pending today. Some of these innovations, for example, those of nanotechnology, bio-medicine, and intelligent machines, have the allure and promise that flying machines had a century ago. The measurement barriers impeding these innovations are as vexing as those encountered by the Wright Brothers. The science and technology enabling these innovations are more complex. The dependence of would-be innovators on the technical infrastructure of the nation, including its measurement system, is, as a result, greater.

The technological innovation that the flying machine was in its day benefited this nation immensely. Other innovations pending today could benefit it as well.

This report is an assessment of the nation's measurement system, aimed at addressing measurement barriers with the goal to accelerate U.S. innovations. NIST hopes through this assessment to contribute to the realization of that goal. I hope that your reading of this report will lead in some way to your contributing to the realization of this goal as well.

Dr. Dennis A. Swyt
Director, NIST USMS Program

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Executive Summary

Introduction

The National Institute of Standards and Technology (NIST) has teamed with the private sector and others to undertake an assessment of the United States Measurement System (USMS), with a focus on technological innovation. The 2005 Council on Competitiveness report, *Innovate America*, notes that, "Innovation will be the single most important factor in determining America's success through the 21st century," and further asserts that the acceleration of innovation is critical for the United States to maintain its competitive edge in the world economy. Technological innovation is taken to be that part of the innovation process relating to the introduction into the marketplace of new technology. Fundamental and potentially transformative technological innovations in nanotechnology, bio-medicine, and intelligent machines hold great promise. Advanced measurement capabilities are essential to innovation in every major economic area and at every stage of the innovation process. Advanced tools and measurements are required to innovate—to design and incorporate new or better features into the kind of next-generation products and processes necessary for the United States to compete effectively and stay ahead in the global marketplace.

The United States Measurement System

The USMS is the complex network of all private and public organizations that develop, supply, use, or ensure the validity of measurements. It is an essential infrastructure, woven into the fabric of our market economy, supporting industry, commerce, government, research, and trade as well as homeland security, defense, health, safety, consumer protection, and other national interests. Encompassing the methods, standards, instruments, and private- and public-sector organizations involved in measurements of products and processes, the USMS is vital to the production and service sectors of the U.S. economy.

In the United States, measurement matters to technology and innovation:

- This year the U.S. semiconductor industry will spend $9 billion on measurement equipment, citing measurement challenges as a major barrier to continued miniaturization of circuits.
- The electric power grid that links the 10,000 generating stations in the United States must be synchronized to within one millionth of one second per day and the Global Positioning System (GPS) to one billionth.
- The U.S. Army requires calibrations traceable to national standards for 58,000 different types of equipment in order to maintain the operational readiness of its weapons systems.
- Improved accuracy of reference measurements for emissions of sulfur in oil refining and steel production has been estimated to have produced $440 million in cost savings and other benefits.
- Software errors due to ineffective testing cost the U.S. economy $60 billion annually.
- The United States spends more than $100 billion per year on measurements in health care, incurring increased costs due to errors in measurement. For example, in a cancer screening trial participants spent an extra $1,000 a year in medical expenses due to false-positive results.

The Assessment Process

This assessment seeks to determine the capability of the USMS to sustain the nation's ever-present need to enhance its performance as a world leader in innovation. NIST undertook several activities from October 2005 to June 2006 to accomplish this goal:

- conducted 15 NIST-industry workshops
- interviewed industry representatives about innovation-impeding measurement problems facing U.S. industry, which were documented as case studies
- reviewed 164 industry technology roadmaps and extracted measurement needs
- contacted executives, in an outreach effort, at more than 100 businesses and trade organizations

In total, more than 1,000 people contributed to this unique assessment of the USMS.

The assessment resulted in the documentation of 723 innovation-impeding measurement problems authenticated by industry. This sample of U.S. industry's unresolved measurement problems is considered to be sufficient to represent measurement barriers impeding technological innovation confronting the USMS. The assessment process consisted of the following:

- content analysis of measurement needs abstracted from industry technology roadmaps
- characterization into various categories of the measurement needs identified in workshops and documented by NIST and industry in authenticated case studies
- application of an inferential analysis methodology to the collected measurement needs, whether derived from roadmaps or case studies
- authentication of the findings from the inferential analysis
- interpretation of the authenticated findings to arrive at judgments about the USMS

Findings from the Assessment Process

Outputs of the inferential analysis process form the basis for findings regarding measurement barriers to technological innovation. Findings were obtained for 11 individual sector/technology areas defined by this assessment and for all the sector/technology areas taken together. These findings were authenticated by representatives of industry to verify their validity, relevance, and significance. This also was done for case-study measurement needs. The findings for all sector/technology areas taken together are the following:

- Fundamentally new measurement technologies are required to overcome limitations of accuracy, which are the most prevalent type of measurement barrier to technological innovation across all sector/technology areas.
- The absence of accurate sensors for real-time monitoring and control of manufacturing processes and environmental conditions poses a significant barrier to innovation that spans multiple sector/technology areas.
- A lack of standards, benchmarks, metrics, and protocols for assessing system-level performance of new technologies, including the compatibility and interoperability of hardware and software systems, is a substantial measurement barrier in a number of sector/technology areas.

Conclusions of the Assessment

Distilled from the full set of 723 measurement needs documented for this study, the conclusions reported here provide a system-wide perspective. They are high-level judgments: about the overall structure of the USMS; about challenges to the system posed by the economic imperative for continuing technological innovation; and about possible responses to those challenges.

The following conclusions, while high level and relatively general in nature, represent a first step toward understanding and addressing system-level weaknesses that diminish the ability of the USMS to support innovation in a rapidly changing technology environment and an increasingly competitive global economy.

Structure and Function of the USMS

- The USMS must provide a national measurement infrastructure for the nation to keep pace with the measurement needs of a growing, rapidly changing, technologically sophisticated economy.
- Novel, multidisciplinary approaches often will be required to meet new types of measurement needs, significantly extending the established USMS structure and paradigm.
- The USMS must evolve in concert with the international measurement system to enable U.S. companies, including technology innovators, to meet the growing number of measurement-based standards that influence access to and transactional efficiency in the global marketplace.

Challenges to the USMS Posed by Technological Innovation

- Measurement innovation (breakthroughs in measurement capabilities) often will be a critical determinant of successful technological innovation in nearly all sectors of the economy.
- The USMS must anticipate and deliver innovations required to meet measurement needs of producers and users of new technology in the manufacturing sector, as well as users of new technology in the service sector.
- To achieve the promise of nanotechnology—an area that may yield the most important technological innovations of the first quarter of the 21st century—major innovations in measurement science and measurement technology are required.
- Successful technological innovation ultimately hinges on the timely availability of production-ready, advanced measurement capabilities.
- The inability to adequately measure system performance (especially the performance of software and information technology hardware) limits the effectiveness and application of new technologies in important service industries.
- New measurement capabilities are required to support emerging technologies for sensing and controlling a wide array of properties and parameters in applications critical to industrial competitiveness as well as to national security and human health and safety.
- Technological innovation has in some cases been stalled due to the lack of measurement technology to assure and verify compliance or to resolve questions regarding potential risks and hazards that emerging technologies may pose.

Responding to USMS Challenges

- Pre-competitive, collaborative R&D is an effective vehicle for addressing needs for new measurement technologies, many of which will have broad utility.
- Federal research organizations and other public-sector organizations that are a part of the USMS will be challenged to prioritize needs within a growing inventory of measurement-related obstacles to technological innovation.
- USMS stakeholders, particularly supporters of fundamental research, need to strengthen the two-way link between advanced measurement capability and the scientific discoveries that become the basis for future technologies.
- The measurement barriers to technological innovation identified in this assessment of the USMS are clear and compelling and call for concerted efforts by the private and public sectors to achieve timely resolution.

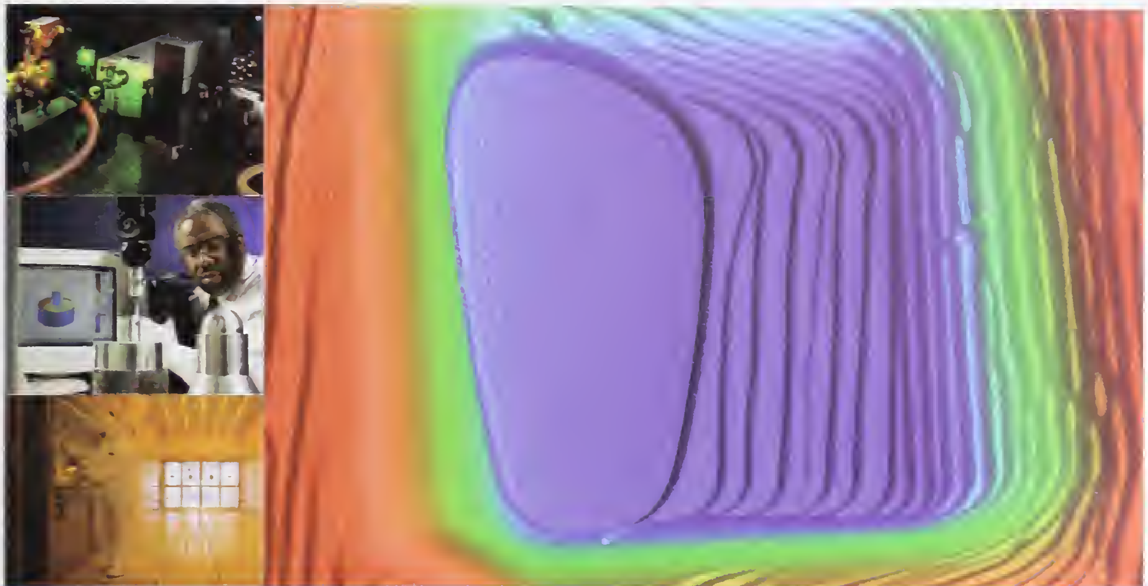
Next Steps

This report makes recommendations for action by all USMS stakeholders, acting individually and in collaboration, to enhance USMS capabilities and, in turn, to accelerate technological innovation. Participation from across the USMS is essential, given the breadth and diversity of the USMS and the challenges it faces. This assessment has identified seven specific actions to be taken as next steps.

NIST, in its unique role as the nation's national measurement institute, has committed to participate in each of the seven recommended actions:

- promoting awareness of critical measurement needs identified in this assessment throughout the measurement research community
- identifying strategies to bolster the effectiveness of USMS solution providers and accelerating development and delivery of measurement technologies that respond to measurement problems impeding innovation
- fostering collaboration to accelerate measurement breakthroughs
- encouraging industrial sectors to identify and prioritize measurement needs
- facilitating pursuit of solutions to specific industry measurement problems documented in this assessment
- identifying shared measurement needs and opportunities for synergy across industries and research areas
- fostering strategic public-sector investments in measurement R&D to accelerate technological innovation by:
  - keeping end users and solution providers informed of federal measurement capabilities
  - incorporating insights from this assessment into strategic and program plans
  - establishing an explicit agenda for measurement innovation

NIST will use this assessment as a means to focus its own work in support of U.S. innovation and competitiveness. It also will partner with other stakeholders in both the private and public sectors to focus organizational, sectoral, and cross-sectoral attention on overcoming the most significant measurement-related barriers to innovation. Feedback on this assessment from stakeholders in industry and government will be solicited and used to improve and guide the next steps described above.



I. Introduction

The ability to innovate and apply new technology is central to our nation's future. In fact, the fiercely competitive global economy demands that innovation become a core competency, not only for businesses and industries, but also for the nation as a whole.

Recent studies have highlighted the critical role played by innovation in science and technology to the continued success of the U.S. economy. The Council on Competitiveness report, *Innovate America*, notes that, "Innovation will be the single most important factor in determining America's success through the 21st century," and further asserts that the acceleration of innovation is critical for the United States to maintain its competitive edge in the world economy.[1]

A recent report published by the National Academies, *Rising Above the Gathering Storm*, notes that, "Although many people assume that the United States will always be a world leader in science and technology, this may not continue to be the case inasmuch as great minds and ideas exist throughout the world. We fear the abruptness with which a lead in science and technology can be lost—and the difficulty of recovering a lead once lost, if indeed it can be regained at all."[2]

In February 2006, President Bush said, "One of the great engines of our growing economy is our nation's capacity to innovate." The situation facing the U.S. economy is summed up in the President's *American Competitiveness Initiative*, which states that, "America's economic strength and global leadership depend in large measure on our nation's ability to generate and harness the latest in scientific and technological developments and to apply these developments to real world applications."[3]

Advanced measurement capabilities are essential to innovation—in every major economic area and at every stage of the innovation process. Research represents the inception of revolutionary technologies of the future; progress in such research depends on advanced measurement capabilities that are fundamental to the exchange of the resulting new knowledge and its refinement into experimental applications.

"One of the great engines of our growing economy is our nation's capacity to innovate."

–President George W. Bush

Ultimately, new, factory-ready measurement tools are essential for cost-effective manufacturing and efficient marketing of leading-edge products and for the integration of these products with other advanced technologies. Advanced tools will be required to design and incorporate new or better features into the next-generation products that will be necessary for the United States to stay ahead in the global marketplace.

To help ensure that these capabilities will be ready when needed, the National Institute of Standards and Technology (NIST) has teamed with the private sector and others to undertake an assessment of the United States Measurement System (USMS) with a focus on technological innovation.

The ability to measure new things in new ways is critical to U.S. industry.

This assessment concentrates on that part of the innovation process that relates to the introduction into the marketplace of new technology. The aim of the assessment is to determine whether the USMS, a vital component of our underpinning technology infrastructure, is adequate to sustain the nation's ever-present need to improve its performance as a world leader in innovation.

Staying ahead in the race to innovate is critical if the United States is to maintain a key competitive advantage, foster productive investment, and create new jobs.

A Defining Moment

This assessment was initiated at an important stage in the evolution of the global economy. Competition in markets for high-value-added products and services is intensifying in two ways—first, as more foreign nations and companies increase their investment in R&D to generate innovative products, and second, as more nations promote their domestic measurements and standards in the global marketplace. Japan has singled out enhancement of its measurement infrastructure as a strategic priority in its science and technology plan for the years 2006–2010. China is proffering its nanotechnology measurement standards for international adoption. The European Union is instituting demanding requirements for assuring the accuracy of measurements used to manufacture certain types of medical equipment and other high-technology products.

Measurements Matter

- This year the U.S. semiconductor industry will spend $9 billion on measurement equipment, citing measurement challenges as a major barrier to continued miniaturization of circuits.
- The electric power grid that links the 10,000 generating stations in the United States must be synchronized to within one millionth of one second per day and the Global Positioning System (GPS) to one billionth.
- The U.S. Army requires calibrations traceable to national standards for 58,000 different types of equipment in order to maintain the operational readiness of its weapons systems.
- Improved accuracy of reference measurements for emissions of sulphur in oil refining and steel production has been estimated to have produced $440 million in cost savings and other benefits.
- Software errors due to ineffective testing cost the U.S. economy $60 billion annually.
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Nanotechnology exemplifies the challenge of the new landscape of global competition on emerging technologies. It is a measurement-intensive and still largely experimental domain. As industries, universities, and government agencies work to master this and other emerging technologies, many organizations are calling for more focused and cooperative efforts to surmount new types of measurement barriers. As interacting technologies and the linkages among organizations grow and diversify, the demand for accurate, reliable measurements will experience proportionate growth. Such measurements will become an integral part of consumer expectations for product performance evaluation in the marketplace. These measurements also will be required to support efficient transactions in markets for future advanced technology products.

The USMS, NIST, and This Assessment

The USMS is the complex of all of the private and public organizations that develop, supply, use, or ensure the validity of measurements. These measurements are vital to the production and service sectors of the U.S. economy. The USMS functions to deliver measurements that meet the nation's measurement needs.

Despite its broad utility and diverse composition, the USMS is usually unseen but is deeply embedded in the nation's commercial technology infrastructure.

Unmet measurement needs—or ineffectively delivered measurement-based services—can slow the progress of research and impede innovation, consequences that undermine the competitiveness of U.S. industry and jeopardize the nation's economic future.

Resolution of measurement needs can speed the progress of research, accelerate innovation, and contribute to supporting the competitiveness of U.S. industry and the nation's economic well-being.

NIST, an agency in the U.S. Department of Commerce, plays a central role in the USMS. By law, NIST is responsible for maintaining U.S. national standards of measurement, a job that the agency and its predecessor (the National Bureau of Standards) have carried out since 1901. As the nation's measurement laboratory, NIST chose to initiate an examination of the USMS, specifically focusing on measurement-related barriers to technological innovation. NIST recognizes that a healthy, effectively performing measurement system is a responsibility shared across the USMS. At the same time, NIST believes that this assessment is clearly needed as an essential step toward ensuring that the USMS remains a valuable contributor to the innovation efforts of organizations and the nation as a whole.

For its assessment, conducted from October 2005 to June 2006, NIST solicited broad input on measurement needs that pose barriers to innovation. For this effort NIST undertook the following activities:

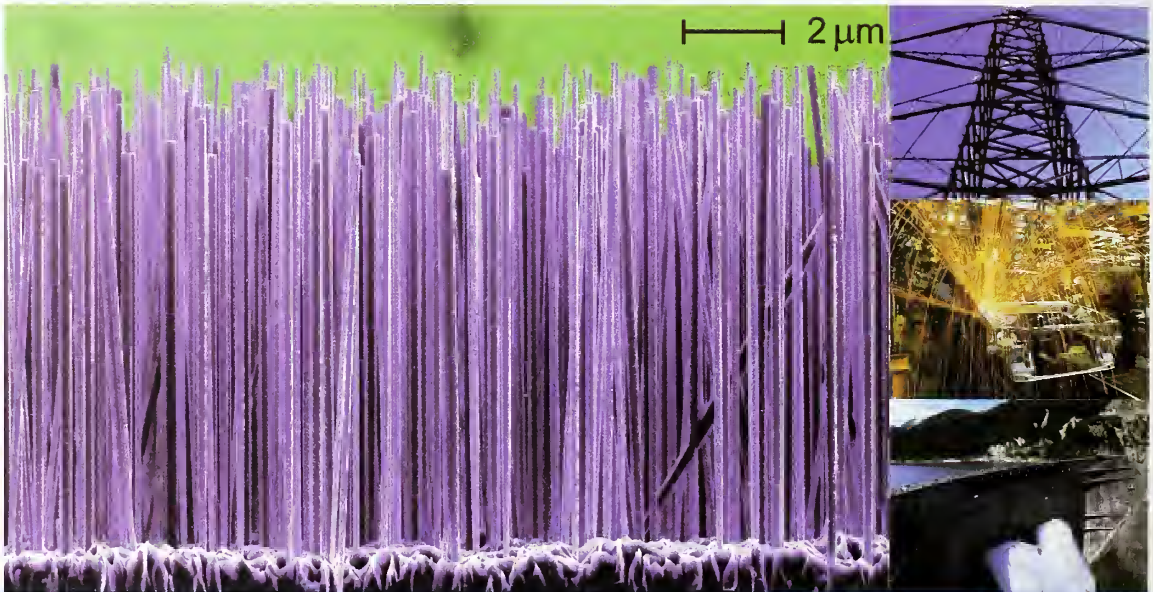
- conducted 15 NIST-industry workshops that engaged more than 500 participants in identifying measurement barriers to innovation (Appendix A)
- interviewed industry representatives about innovation-impeding measurement problems facing U.S. industry which were documented as case studies (Appendix B)
- reviewed 164 industry technology roadmaps and extracted measurement needs (Appendix C)
- contacted executives, in an outreach effort, at more than 100 businesses and trade organizations

In total, more than 1,000 people contributed to this unique undertaking (Appendix D).

The remainder of this report provides an overview of the USMS, describes the methodology of the assessment, presents the results of the assessment, and details the follow-up actions that NIST intends to take in response to the assessment. The full report is available on the NIST Web site at http://usms.nist.gov.

Unmet measurement needs can slow the progress of research and impede innovation.

Resolution of measurement needs can accelerate innovation.



II. Purpose and Elements of the USMS

The USMS is an essential infrastructure, woven into the fabric of our market economy and society. It supports industry, commerce, government, research, and trade as well as homeland security, defense, health, safety, consumer protection, and other national interests.

In terms of technological innovation and economic growth, the USMS provides, or enables, measurement capabilities, tools, and services that are employed throughout the process of innovation. This process ranges from research (the source of new knowledge) to the diffusion of new ideas and nascent technologies and, ultimately, to the production and sale of new products and services that embody the results of the innovation process.

The USMS is essential to the function and performance of the national economy.

In this assessment, the USMS is taken to include the methods, standards, instruments, and private and public organizations involved in measurements of products and processes or in other measurement-related activities relevant to the function and performance of the national economy. It includes both measurement suppliers and users, two broad categories with many divisions notable for both their variety and their vastly different requirements. Measurement and related terms are defined in Figure 2.1.

For clarity, it is important to distinguish between the USMS and a necessary core element common to all industrialized economies: the National Measurement System (NMS). Previous studies of the economics of measurement, undertaken in the United States and several other nations,[4] focused almost exclusively on the NMS within these countries.

As depicted in Figure 2.2, the NMS is situated within—and operates in support of—the broader USMS. In the United States, as elsewhere, key functions of the NMS are 1) to ensure the reliability and uniformity of measurement results, as is required for orderly markets and technological innovation; and 2) to enable comparability of

measurements through linkages to the international measurement system, as is required to integrate the United States with the global economy.

Key elements of the NMS and several other components of the USMS, as shown in Figure 2.2, are discussed in the remainder of this chapter. In the context of technological innovation, the scientific research enterprise plays an especially critical underpinning role within the USMS. Also as indicated in the figure, the ultimate effectiveness of the USMS depends on private- and public-sector inputs and participation, as well as on cross-sector collaboration.

International System of Units

Most measurements made for economic purposes quantify properties of "things." Such measurements are primarily rooted in physical mechanisms and processes described by the laws of physics.

The International System of Units (SI) is globally accepted. Its goal is to define a system of measurement units directly based on quantities of nature that do not vary with time or circumstance (e.g., the meter—the unit of length—is defined in terms of the speed of light). Basing the SI on the laws of physics provides an unambiguous reference for comparison, and it facilitates the dissemination of accurate measurements in commerce, industry, and science.

The SI is the modern descendant of the 1875 Convention of the Meter, a treaty that included the United States as the second of 17 original signatory nations. The modern SI dates back to the early 1960s. Both metric and customary units are presently legal and in use in the United States.

The Convention of the Meter also established the International Committee for Weights and Measures (CIPM) and the International Bureau of Weights and Measures (BIPM), which are charged with ensuring worldwide uniformity of measurements and traceability to SI units, and with improving the SI. The CIPM fulfills these responsibilities through a series of Consultative Committees. Committee members are representatives of national measurement institutions from the signatory nations of the Convention. In addition, the BIPM, headquartered near Paris, France, performs its own laboratory work. As the fields of science and technology advance, values of existing units are refined and new derived units may be established, all by international agreement through the General Conference on Weights and Measures.

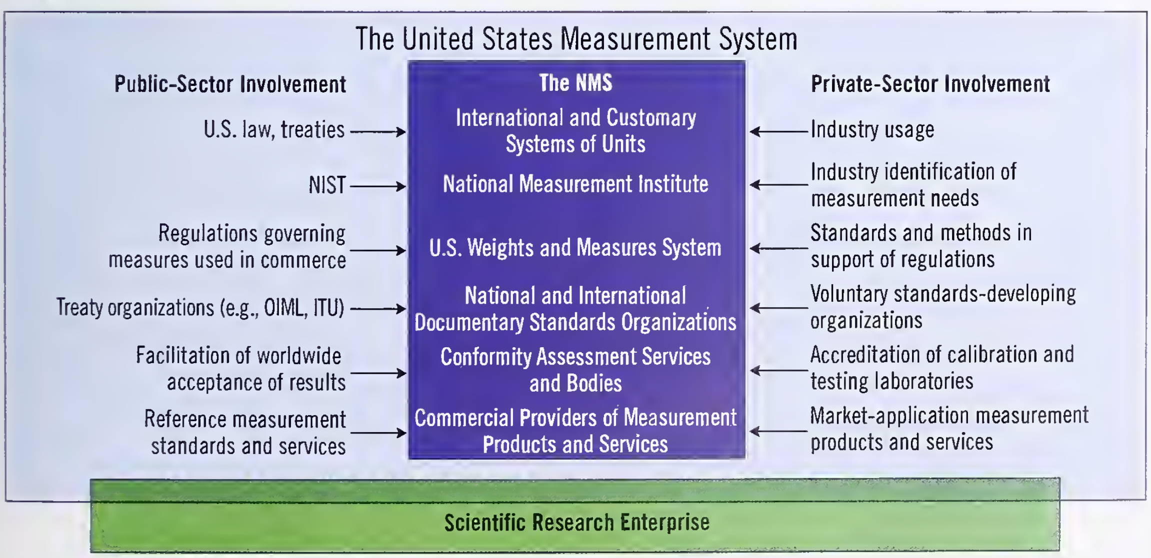
Figure 2.1. Useful Terms

Measurement: The process of quantitatively comparing a variable characteristic, property, or attribute of a substance, object, or system to some norm.

Measurement result: The quantitative result of the measurement process, achieved to a level of certainty influenced by a combination of technical and human elements that include measurement methods, instruments, information, standards, and institutions.

Measurement system: The entire set of technical and human elements involved in producing measurements for an intended purpose.

Figure 2.2. The USMS and the NMS Within It



Measurement traceability and comparability across nations also is facilitated through bilateral and multilateral agreements and through Regional Metrology Organizations (RMOs), such as the Inter-American Metrology System (SIM) and the Asia Pacific Metrology Program (APMP). NIST serves as the U.S. representative in SIM.

National and International Documentary Standards Organizations

An estimated 80 percent of world trade is influenced by standards for products, processes, and systems, as well as by regulations embodying these standards. In turn, measurement-related requirements (and specified tests or inspections for demonstrating compliance with those requirements) are significant components of most standards and regulations.

The SI is the globally accepted system of units of measurement.

Documentary standards development in the United States is led by the private sector, aligned with industry sectors, and largely demand driven. Individual standards are typically developed in response to specific concerns and constituent issues expressed by both industry and government. Government agencies are major users of standards, in both regulation and procurement. Agency representatives also participate in the development of all kinds of voluntary standards, including test methods, specifications, and other measurement-related standards.

While there are more than 450 standards-developing organizations (SDOs) in the United States, about 20 of these develop 80 percent of the standards in use by both the private sector and government. Many of these documents have a substantial measurement component.

Some U.S.-domiciled organizations develop standards that are used globally to meet specific sector needs, including electronics and materials standards, boiler and pressure vessel codes, and specifications for piping and fuels. These organizations include the Institute for Electrical and Electronics Engineers (IEEE), ASTM International, the Society of Automotive Engineers, ASME International, the Aerospace Industries Association, and American Petroleum Institute, among others. Membership in these organizations is on an individual or organizational basis.

International measurement-related documentary standards also are developed by treaty organizations (with governments as members); private, voluntary organizations with memberships composed of national entities; and consortia and forums, whose memberships are typically company and industry based. These include the following organizations:

- The International Organization of Legal Metrology (OIML) is a treaty organization that develops model international standards pertaining to measurements used for regulatory purposes, such as commodity exchange and environmental monitoring.
- The International Telecommunications Union (ITU) is a treaty organization that focuses on standards for information and communications technologies.
- The International Organization for Standardization includes the national standards bodies of 149 countries and develops standards for nearly every industrial sector.
- The International Electrotechnical Commission (IEC) focuses on electronics standards.

The United States is prominently involved in standards activities conducted in each of these organizations. NIST is the technical representative to OIML, on behalf of the Department of State. The State Department represents U.S. interests directly in ITU. U.S. interests in ISO and IEC are represented by the American National Standards Institute (ANSI), a federation of SDOs, companies, trade associations, government agencies, and consumer groups.

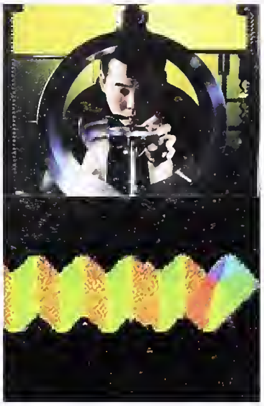
National Measurement Institute

By federal statute, NIST is the National Measurement Institute (NMI) of the United States, responsible for national standards of measurement and, within the SI framework, for their compatibility with the standards of other nations. To achieve international compatibility in measurement, NIST works with its counterpart NMIs. These government-established entities exist in nearly every nation.

The role of NIST as an NMI is multifaceted:

- representing the United States in the Consultative Committees of CIPM and in SIM
- establishing, maintaining, and disseminating national standards of measurement, basing them on its realizations of SI units and linking them globally through international comparisons conducted with other NMIs
- collaborating with BIPM and other NMIs to ensure that realizations of the definitions of the base SI units—and those units derived from these base units—have accuracies that stay ahead of industrial needs
- providing U.S. industry, the scientific community, and federal, state, and local governments with access to national standards of measurement, often at the highest level of accuracy in the world. This is accomplished through research and the resulting measurement services:
  - calibration of customers' precision measuring instruments and physical standards
  - provision of reference materials of the highest metrological quality
  - provision of evaluated reference data
  - provision of measurement science results that enable new measurements and the development of new measuring instruments

NIST's maintenance of base SI units (length, mass, time, electric current, temperature, amount of substance, and luminous intensity) and a growing number of derived units underpins private-sector investments in measurement technology and standards. Realizations of these units provide the necessary means for assessing the quality of the myriad measurements made daily during the design, production, inspection, and sale of goods and services. They provide benchmark references for so-called second- and third-tier suppliers of measurement services, instruments, and related products, as well as for the users of these measurement solutions. Examples of these suppliers and users include private-sector test and calibration laboratories, manufacturers of measurement tools and control systems, and the businesses that rely on these services and tools. Additional details of NIST's realization and dissemination of the units of the SI are provided in Appendix E.



In 1999 NIST was one of the original signatories to the CIPM Mutual Recognition Arrangement. This agreement set a framework for establishing the degree of equivalence of measurement standards maintained by NMIs worldwide. A key objective was to assure that measurement results traceable to different NMIs could be accepted across international borders, thereby improving transactional efficiency and eliminating potential regulatory burdens and technical barriers to international trade.

U. S. Weights and Measures System

The U.S. Weights and Measures System, a subset of the USMS, is stipulated in the U.S. Constitution. It is composed of organizations that make, use, and ensure the validity of measurements involved in the buying and selling of products and services on the basis of weight, measure, or count. These commercial transactions account for about half of the U.S. economy. The U.S. Weights and Measures System facilitates fairness in the marketplace. It enables accurate weighing and measuring devices, from truck scales and parking meters to gasoline pumps and price scanners.

The system includes the following key elements:

Commercial transactions based on weight, measure, or count, make up about half of the U.S. economy.

- scale and meter manufacturers, consumer product manufacturers, retailers, consumer agencies, and government agencies
- an extensive network of local and state weights-and-measures programs
- the National Conference on Weights and Measures (NCWM), a private, nonprofit organization with representatives from industry, the states, and the federal government, develops standards, test procedures, and model laws and regulations on weights and measures
- NIST, which provides technical assistance to the NCWM as it develops standards, regulations, and methods of practice

Except for the following federal responsibilities, laws and regulations governing weights and measures used in commerce are generally created—and enforced—at state and local levels. However, the NCWM works to achieve uniformity across jurisdictions to reduce barriers to interstate commerce.

At the federal level, Congress has assigned weights-and-measures regulatory authority to three organizations:

- U.S. Department of Agriculture, for the export of meat and poultry products and grains
- Food and Drug Administration, for pharmaceutical safety and labeling
- Federal Trade Commission, for product labeling and advertising

At the international level, OIML oversees efforts to promote harmonization of performance requirements for measuring instruments that are subject to laws or regulations.

Conformity Assessment Services and Bodies

Sampling and testing, inspection, product certification, and other conformity assessment procedures provide a means of ensuring that products, services, or systems meet customer or regulatory requirements. These procedures also provide assurance of consistency from product to product, service to service, or system to system. Other examples of conformity assessment include quality and environmental system assessments and registrations as well as formal programs for accrediting the competence of organizations that provide conformity assessment services. Evaluation and recognition of the capabilities of accreditation programs comprise another aspect of conformity assessment.

Each of these activities is a distinct operation, but they are closely interrelated. Conformity assessment activities form a vital link between standards and products. These standards typically define necessary characteristics or requirements for products and specify tests and measurements for achieving and demonstrating compliance.

Conformity assessment in the United States is complex, multifaceted, and decentralized, with more than 100 organizations accrediting calibration, measurement, and testing laboratories. Unfortunately, businesses that use the services of accredited laboratories often find that the results are not universally recognized. Consequently, one customer may require a business to demonstrate conformity with requirements through testing done by a laboratory accredited by a specific organization, while another customer may stipulate a testing laboratory with a different accreditation.

Three U.S.-based organizations—the International Accreditation Service, National Voluntary Laboratory Accreditation Program, and American Association for Laboratory Accreditation—along with 49 other laboratory accreditation bodies from 42 economies around the world, are signatories to the International Laboratory Accreditation Cooperation (ILAC) Mutual Recognition Arrangement (MRA). Signatories accept, on the basis of a peer evaluation process, that the accreditations granted by other signatories are accomplished through a process that is in conformance with internationally accepted standards and practices. Further, signatories promote the acceptance of calibration, testing, and/or inspection results within the respective scopes of accreditation for laboratories accredited by any of the MRA signatories.

The aim of the ILAC MRA is to develop a global network of accredited testing, calibration, and inspection facilities that can be relied on to provide accurate data. To that end, ILAC and the CIPM signed a memorandum of understanding in March 2005, recognizing the important link between accreditation and traceability to national standards. ILAC's ultimate aim is increased use and acceptance by industry as well as government of the results from accredited laboratories, including results from laboratories in other countries so that a product tested once can be accepted everywhere.

Commercial Providers of Measurement Products and Services

Given the scale and diversity of the U.S. economy, the number of businesses that provide measurement products and services is proportionately large. The composition of this hybrid sector is commensurately diverse and includes the following:

- commercial suppliers of measurement standards
- measurement, calibration, and testing laboratories and services
- suppliers of measurement instruments and devices
- measurement consulting and training services

Because of the tremendous variety of test and measurement tools and services required to support the U.S. economy, no single industrial classification encompasses all the businesses that supply these tools and services. Specific segments within the "measurement sector" range from manufacturers of process control equipment to makers of meters for measuring consumption of water, gas, or electricity, and from suppliers of laboratory analytical equipment to makers of tools for inspecting semiconductor wafers and measuring the thickness and quality of thin films. Figure 2.3 provides examples of selected measurement instrument industries and their characteristics.

The measurement-intensive nature of processes and the required levels of measurement accuracy vary considerably across industries. Generally speaking, the more advanced and complex the technologies incorporated into a commercial product, the greater the need for measurement support.

For example, a NIST study found that the semiconductor industry spent about $5 billion on measurement (not including labor and overhead) in 2001. This investment has been growing at a rate of about 15 percent per year, raising this expenditure to an estimated $9 billion in 2006.

Assuming that the nation's entire high-technology sector invests about the same percentage on measurement as does the semiconductor industry, it would have spent about $70 billion on measurement in 2004.

The semiconductor industry alone will spend an estimated $9 billion on measurement in 2006.

Scientific Research Enterprise

The scientific research enterprise forms the foundation of the USMS, while also serving as an element of the USMS. Science is, to a large extent, the quantitative, predictive description of the observable behavior of the things of the physical world. Science rests on measurement. Measurement rests on science. The discoveries of science enable and propel advances in measurement technology. Advances in measurement technology enable and propel advances in science. Research and advances in the most basic sciences—physics, biology, chemistry—and in measurement science proceed in tandem. And, most importantly, technological innovation rests on the availability of and access to new knowledge that is produced primarily by scientific research.

Several principal elements of the U.S. scientific research enterprise are foundational elements of the USMS:

- mission-directed fundamental research in measurement science conducted by NIST and other parts of the research enterprise
- curiosity-driven basic research in science conducted by universities
- mission-directed applied research conducted by government agencies
- business-directed applied research conducted by industry that they report publicly
- measurement-technology R&D conducted by government agencies, including NIST
- measurement-technology R&D conducted by industry that it reports publicly

The USMS has been described here as a complex system of independently operating entities. Given this description, how should an assessment of the USMS be conducted? What should it include? Chapters 3 and 4 provide the parameters of this assessment of the USMS, along with the methodology used to conduct it.

Figure 2.3. Examples of Measurement Instrument Industries, 2004*

Industry	No. of Companies	Value of Shipments
Aeronautical, Nautical, & Navigational Instruments	86	$2.4 billion
Analytical & Scientific Instruments (except optical)	296	$8.8 billion
Automatic Valves	154	$2.2 billion
Equipment for Testing Elec., Radio & Comm. Circuits, & Motors	310	$9 billion
Process Control Instruments	481	$6.5 billion

* Economic and Statistics Administration, U.S. Census Bureau, *Selected Instruments and Related Products: 2004; Current Industrial Reports*, August 2005.

III. Focus on Innovation: The Importance of Measurement

"The United States achieved global leadership in innovation in the 20th century. And the capacity to innovate is the foundation for bringing our competitiveness into fruition."

National Summit on Competitiveness 2005

Technological innovation drives the nation's economic growth and sustains U.S. competitiveness in world markets. In nearly all industrialized nations, progress in developing and applying technology drives growth in economic output (gross domestic product). According to economic studies—beginning with those of Nobel Laureate Robert Solow—technology accounts for more than half of U.S. economic growth in the last 60 years. Statistics within the United States mirror this fact. Growth and productivity represent the primary means of increasing national prosperity, and new technology has fueled about 75 percent of growth in U.S. productivity. And since the mid-1990s, technology has been credited with driving an even larger share of productivity gains.

As international competition increases, technological innovation has become the chief differentiator for U.S. industry, a source of comparative advantage to counter low-cost manufacturing or labor. However, more and more developed and developing nations recognize that improving their technological performance is key to future economic growth. Many of these countries are rapidly ascending from the ranks of imitators to become innovators.

Recognizing the strategic importance of technological innovation, NIST's assessment of the USMS looks at unmet measurement needs that impede our ability to develop and commercialize new technology. The pivotal role that innovation will play in the nation's economic future is underscored by the President's American Competitiveness Initiative and in a growing collection of evaluations of U.S. prospects for sustaining technology-driven economic growth. Nearly all have concluded that innovation will be vital to the nation's economic success.

Innovation will be the single most important factor in determining America's success through the 21st century.

A focus on innovation, however, does not fully capture other vital functions and contributions of the USMS. For example, measurement needs tangential to innovation may be key to furthering the mission-related goals of federal agencies or to improving safety, health, and other determinants of the nation's well-being.

Unmet measurement needs impede our ability to develop and commercialize new technology.

U.S. industrial competitiveness is necessary to sustain long-term economic growth. Technological innovation, in turn, is critical to industrial competitiveness and to the degree of productivity growth necessary for U.S. citizens to improve their standard of living. Both benefits serve the national interest and warrant the focus on innovation of this initial USMS assessment.

The Role of Measurement in Innovation

The underpinning or infrastructural role of advanced measurement capabilities is multifaceted. Every phase of research and development (basic and applied research and exploratory development) and the subsequent manufacturing and commercialization stages of innovation require measurement tools and related standards. During the discovery stage, accepted measurement methods are necessary for interpreting, communicating, replicating, and extending the results of research. At the commercialization end of the spectrum, the role is just as significant. Market acceptance of new high-technology products may be contingent upon the availability and acceptance of test and measurement methods necessary to verify product performance claims.

Technological innovation is critical to U.S. industrial competitiveness and long-term economic growth.

For example, a communications services company requires a range of testing standards to determine whether the thousands of kilometers of ultra-thin optical fiber it purchases will meet specifications for an assortment of performance attributes, such as bandwidth, signal-loss rates, and core-diameter consistency. Without such measurement capabilities, which are essential to sellers and buyers alike, growth of emerging high-tech industries would be hampered. Lack of measurement capabilities results in transactional inefficiencies that delay market acceptance and eliminate the "first-mover" advantage of innovating firms.

Methods of measurement, analysis, testing, and evaluation, along with relevant standards and related databases, function as "general-purpose technologies," valuable for their impact on the effectiveness, efficiency, and productivity of the innovation process. Like electricity and information technology, two of the most widely recognized general-purpose technologies, measurement tools have broad utility but can be leveraged in different ways. For example, new measurement capabilities enable the following:

- making it easier to invent and produce new products and processes
- working across functions to be adapted, enhanced, or extended, serving multiple uses, such as research and production, and they can be applied to a wide variety of commercial products and services
- enabling communication across stages of the innovation process and among collaborators
- increasing in value and utility as they diffuse more broadly within industries and across sectors
- complementing existing and emerging technologies

Although less apparent than electricity and information technology, measurement tools are just as ubiquitous. The capabilities that these tools enable may mean the difference between success and failure in realizing the promise of emerging technologies. That is, the ability to measure accurately, reliably, and cost effectively can set the

limits on what can be accomplished in the laboratory, on what can be realized on the factory floor, and on which products can be marketed at affordable prices. In short, what gets measured is often what gets done.

The most recent International Technology Roadmap for Semiconductors (2005) helps to illustrate this increasingly vital link between measurement and successful innovation. According to this roadmap, "As the industry moves further into the world of nanoelectronics, metrology,[5] including materials characterization, will take on greater challenges and become even more critical."[6] Examples of these challenges include measuring materials properties at subatomic dimensions and achieving control of atomic dimensions while maintaining profitable high-volume manufacturing.

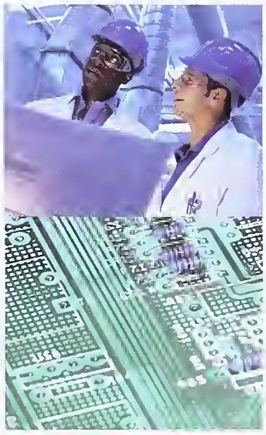
Similar challenges confront many industries, many companies, and many laboratories—not just those aiming to control, manufacture, and assemble at the scale of atoms and molecules. The more than 700 measurement needs identified in this initial assessment of the USMS serve as compelling evidence that new or improved measurement capabilities are a collective requirement for leadership in innovation.

Technological Innovation and Measurement Innovation

In this assessment technological innovation is considered to be either a process or a physical entity. As a process, technological innovation is that part of the overall innovation process relating to the introduction into the marketplace of new technology. As a physical entity, technological innovation is the new technology itself.

Technological innovation is considered to occur in four stages. This conceptualization is consistent with that of a consensus of economists and is akin to others used to characterize product development. It shares with them limitations in representing the non-sequential, iterative, and conceptually messy processes of the real world. The four stages of technological innovation are:

- *applied research* specifically directed at realization of a particular new technology and encompassing invention and development of a prototype, if appropriate
- *production* to implement the processes for producing market quantities of the new technology as future product
- *market placement* of the new technology as product
- *end use* of the new technology product for its intended purpose



These stages of technological innovation are considered to be informed by what this report calls a technology developer's vision. This vision is the conceptual view of what the new technology will functionally do, who the user of the new technology will be, and what benefit to the user that new technology will yield. Central to the story of the Wright Brothers' encounter with a measurement barrier to technological innovation, cited in the foreword of this report, is their technology developer's vision—a machine for powered, controlled, heavier-than-air human flight.

Figure 3.1 illustrates the process of measurement innovation for addressing measurement barriers to technological innovation. Shown are the process of technological innovation, the

process of measurement innovation, and the relationship between the two when a measurement barrier occurs at a particular stage of technological innovation. If the measurement technology necessary to solve that problem does not exist, a measurement innovation is needed. Because a measurement innovation is itself a technological innovation, the measurement innovation process is the same as that for the technological innovation. It involves successively, applied research, production, market, and end use of the new measurement technology.

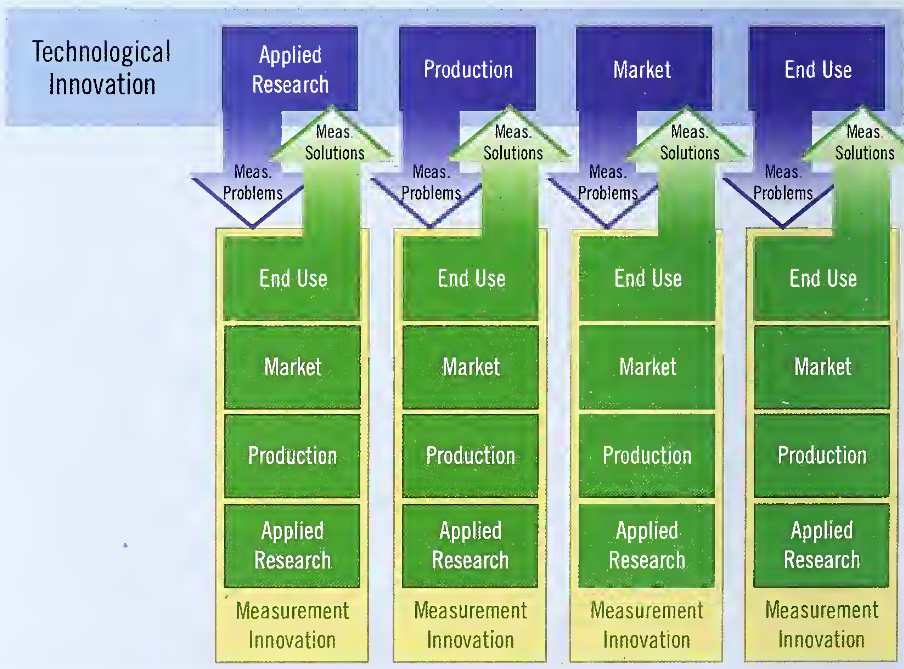
Roles of the Public and Private Sectors

In the United States, the public and private sectors play different, yet complementary, roles in the process of technological innovation:

- The public sector (government) supports basic research, which generates the new knowledge and scientific discoveries upon which new technologies ultimately are based.
- The private sector (industry) develops and commercializes technology.
- The public and private sectors jointly contribute to enhancing the technical infrastructure, including the USMS, that supports technological innovation.

The U.S. government seeks to create an environment that encourages investment in the pursuit of new technologies and helps to reduce shared barriers to innovation. Unaddressed measurement needs can impede the nation's innovation performance. Through this assessment, NIST aims not only to identify measurement problems that pose barriers to innovation, but also to identify steps toward effective solutions.

Figure 3.1. The process of measurement innovation for addressing measurement problems that pose barriers to the process of technological innovation



IV. Methodology of the Assessment

Information Gathering

This assessment of the USMS is based on the identification and analysis of measurement problems that confront U.S. industry and pose barriers to technological innovation. Each measurement problem represents a current, unmet industry measurement need.

The set of measurement needs identified for this assessment, while a sampling, nevertheless is sufficiently representative to yield good indicators of the USMS as a whole.

NIST identified hundreds of industry measurement needs across selected industries (sectors) and technology areas considered to be significant to the U.S. economy—either today or in the future.

This chapter summarizes the methodology that was used to identify, characterize, and analyze these measurement needs within and across sectors and technology areas. A detailed description of the methodology is contained in Appendix F.

Identification of Measurement Needs

The information used to document each measurement need was gathered from one or more of the following sources:

- published industry technology roadmaps
- USMS-affiliated industry workshops convened by NIST and other organizations to identify measurement problems in specific sectors or technology areas
- various combinations of industry reports, technical publications, and interviews, as documented by NIST staff
- submissions by individuals or organizations within specific industries

Submissions were solicited by NIST through outreach efforts to senior executives in 120 measurement-related industry, trade, standards, and professional organizations. NIST informed these executives of the USMS effort and invited participation to indicate industry measurement needs or authenticate measurement needs or findings. NIST also solicited input through news announcements, its USMS Web site, and briefings to various industry audiences.

Because technological innovation spans a broad range of activities—from basic research to product and process development and beyond—and often draws on the efforts of many individuals and organizations, measurement needs were pursued from four points of view, described below. The objective of this multiple-view sampling was to achieve a wide-angle snapshot of measurement barriers to technological innovation across a breadth of industries and technologies.

- **Industrial Sectors:** Three sectors—automotive, semiconductors, and IT software—were selected to generate a sample of industry-specific measurement needs. The industries that make up this sampling are economically and socially important as they depend heavily on technological innovation and are known to have measurement barriers to innovation.
- **Technologies:** Four broad technologies—nanotechnology, disaster first responder technology, biomedical imaging, and magnetic data storage[7]—were selected for the sample of technology areas. (See Appendix G.) These areas were selected because of their dependence on innovation, potential to yield numerous commercial applications, or relevance to important national needs.
- **Scientific and Engineering Disciplines:** Seven disciplines were selected—physics, chemistry, materials science, electrical and electronic engineering, mechanical and civil engineering, manufacturing engineering, and computer science and engineering—on the basis of their foundational relationships to new product and process technologies.
- **International System of Units (SI):** The units of the SI—both base units (length, mass, time, electric current, temperature, amount of substance, and luminous intensity) and derived units—were selected because of their centrality to the spectrum of measurements performed in industry, commerce, and science. (See Appendix E.)

Regardless of the sector, technology, discipline, or SI unit taken as the vantage point for identifying measurement problems that pose barriers to technological innovation, all participating scientists, industry representatives, and technology experts were presented with the same challenge whether they participated in workshops, abstracted technology roadmaps, or otherwise represented a measurement need. All were asked to respond to the following question: "From your position in this sector (be it an industry, technology area, scientific-engineering discipline, or field of measurement), what industry measurement problems do you see that pose barriers to technological innovation?"

Documentation of Measurement Needs

Basic units of input to this report are measurement needs, defined as unresolved industry measurement problems that pose technical barriers to economically important technological innovations. As mentioned previously, these measurement needs were identified in industry technology roadmaps; in workshops; in NIST staff syntheses from various combinations of industry reports, technical publications, and interviews; or in submissions by individuals outside NIST. Measurement needs from the latter three sources were documented following a standardized reporting format. The data fields of this format are listed in Figure 4.1.

Within this report, these one-page, stand-alone measurement need summaries are referred to as case studies. These case-study measurement needs appear in Appendix B.

Measurement needs abstracted from published technology roadmaps could be summarized in general terms only, as they were documented prior to this assessment, not documented explicitly for this purpose, and, in many cases, not detailed in information for all the fields in the case-study format.

Authentication of Measurement Needs

Measurement needs reported and analyzed in this assessment have undergone authentication. That is, they were independently verified as valid, relevant, and significant.

For measurement needs distilled by NIST technical staff, the facts asserted were authenticated by multiple sources external to NIST. These sources included the following:

- industry representatives and/or technology experts selected for their knowledge of the specific industry or technology in question
- public domain documentary references, including technology roadmaps
- reports from workshops having broad industrial representation

Measurement needs abstracted from industry technology roadmaps were considered to be self-authenticated. Each roadmap was produced by a group representative of that particular community and knowledgeable about the specific industry or technology area in question.

Measurement needs derived from USMS-affiliated, industry-needs workshops were considered to be self-authenticated. As a group, participants in each workshop met the criteria for authenticators. By design and mix of interests, the workshop groups were knowledgeable and representative.

Analysis of Gathered Information

The principal results of this assessment are based on several types of analyses of identified industry measurement needs:

- content analysis of measurement needs abstracted from industry technology roadmaps
- characterization into various categories of the case-study measurement needs identified in workshops, documented by NIST staff, or submitted by individuals outside of NIST
- inferential analysis of all the collected measurement needs, whether derived from roadmaps or case studies and whether derived from the perspectives of sectors, technologies, disciplines, or SI units
- authentication of the findings from the inferential analysis
- interpretation of the authenticated findings to arrive at judgments about the USMS

Content Analysis of Measurement Needs Abstracted from Industry Technology Roadmaps

An industry technology roadmap analysis was conducted. (See Appendix C.) Through the analysis process, the set of measurement needs derived from industry technology roadmaps was examined, trends in measurement needs within sectors were evaluated, and a review probing for key themes, synergies, and commonalities across sectors was performed.

Figure 4.1. Data Fields for the Case-Study Measurement Needs

- Technology at Issue
- Submitters
- Technological Innovation at Stake
- Economic Significance of Innovation
- Technical Barrier to the Innovation
- Stage of Innovation Where Barrier Appears
- Measurement-Problem Part of Technical Barrier
- Potential Solutions to Measurement Problem

Characterization Analysis of Case-Study Measurement Needs

The measurement needs documented as case studies were analyzed according to various characteristics within seven major categories. (See Appendix B.)

- **Economic Sector/Technology Area:** In what part of the economy does the vision exist for the development of the particular technological innovation?
- **Stage of Technological Innovation:** Where along the spectrum, from applied research on a concept to end use of the product, is the technological innovation planned?
- **Is the Technological Innovation at Stake a Measurement Technology?** Is a new measurement technology the planned technological innovation?
- **Measurand:** What type of quantity is being measured?
- **Measurement Problem Posing Technical Barrier:** What is the measurement-related portion of the technical barrier that is inhibiting the technological innovation?
- **Potential Measurement Solution(s):** What possible routes can be followed to solve the measurement-problem part of the technical barrier?
- **Potential Solution Provider(s):** What private or public organizations, groups of organizations, and individuals might contribute to solutions to the measurement-problem part of the technical barrier?

Figure 4.2. Sector/Technology Areas

- Building and Construction
- Chemicals
- Defense and Homeland Security
- Discrete-Parts Manufacturing Including Automotive
- Electronics and Information Technology (IT) Hardware
- Energy, Power, and Environment
- Health Care Including Bioimaging
- IT Software
- Materials
- Nanotechnology
- Semiconductor Electronics

Case-study measurement needs were first categorized according to *sector/technology area*, which encompasses the combination of the economic sector or the technology area with which a particular technological innovation is associated, as shown in Figure 4.2.

Next, the measurement needs within each sector/technology area were categorized according to specific characteristics of the data fields—*Measurement Problem, Solution to the Measurement Problem*, and *Potential Solution Providers*. These specific characteristics are listed in Exhibit 3 of Appendix F.

The categorized set of all case-study measurement needs was sorted, tabulated, and correlated according to the data fields mentioned above. The resulting statistical data and the content analysis of the industry technology roadmaps were used as the basis for making inferences about measurement barriers to technological innovations and the USMS.

Inferential Analysis Process

As the basis of its assessment of the USMS, NIST developed an inferential analysis process consisting of these steps:

- examining the case-study and roadmap measurement needs and the results of statistical and content analyses to identify significant features and patterns within and among those measurement needs
- extracting facts from and making factual statements about those features and patterns
- using informed judgment to interpret the meaning and significance of those factual statements

- making declarative statements based on the factual statements as so interpreted
- identifying some declarative statements as being based on a sufficient number of documented measurement needs and supported by sufficient fact and logic to qualify as potential ***findings*** and submitting them for authentication by industry representatives
- identifying other declarative statements as not meeting the standard of a potential finding but representing a potentially significant measurement issue and submitting it for review by industry representatives as ***other observations***

This process for generation of potential findings was applied to each of the 11 sector/technology areas, as well as to the aggregated group of all the measurement needs from each sector/technology area. In each case, a small group of NIST technical staff knowledgeable about that area was convened to participate in the inferential analysis process.

The process was applied in rounds, focusing in turn on the following areas:

- barriers, providers, and solutions
- measurands (i.e., the quantities measured) and cases where the technological innovation was a measurement technology
- stage of technological innovation
- technology developer's vision and cross-sector aspects

There was neither an upper nor a lower limit to the number of findings in each round. Rather, the number of findings, and the rounds in which they were noted, varied across the sector/technology areas, as the data supported them. The final round asked the participants in the inferential analysis to list challenges to measurement innovation and the operation of the USMS that were noted during the analysis.

Authentication of Findings

The findings of this assessment report are those findings that resulted from the inferential analysis process that were subsequently authenticated. As with the case-study measurement needs, the findings were vetted with individuals outside NIST who were considered to be knowledgeable and representative of a particular sector/technology area. Authenticators, working in a web-based environment, reviewed and commented on each of the findings within a specific sector/technology area. Findings based on the entire set of measurement needs were similarly authenticated.

Interpretation of Findings

The outputs of the inferential analysis form the basis for the principal results of this assessment, which are, first, authenticated findings on measurement barriers to technological innovation and, second, conclusions about the USMS as it relates to those barriers. These ***conclusions*** are judgments about the capacity of the USMS to address the identified measurement barriers to technological innovation. They are based on an examination of the findings, the measurement needs, the analysis of them on which the findings are based, and the overall context of technological innovation within the United States.

V. Results of the Inferential Analysis

This assessment of the USMS by NIST was based on measurement needs—unresolved measurement problems, such as insufficient accuracy and resolution or lack of production-ready techniques—that pose barriers to technological innovation. The assessment consisted of three types of analyses that yielded results at different levels of specificity:

- actual measurement needs that were tabulated, categorized, and correlated to enable identification of patterns within and across categories of unmet measurement needs
- findings about measurement problems within the 11 industry sectors and technology areas (referred to as sector/technology areas)
- findings about measurement barriers for all sector/technology areas taken together

Measurement Needs

This assessment has documented 723 specific industry measurement needs that pose technical barriers to technological innovation. This collection of measurement needs is the product of two different sampling methods.

The first method utilized industry technology roadmaps that provided a broad perspective on the scientific and technical research needed to support future technological progress. Incorporating the views of representatives from industry, academia, and, often, government, the roadmaps are consensus documents identifying targets of opportunity and barriers to envisioned technologies in a particular industry. In all, 164 industry technology roadmaps, published from 2000 to 2006, were reviewed for statements of measurement needs. Of these, 82 percent (135) identified measurement problems that pose barriers to technological innovations in their industry. These 135 roadmaps provided 386 of the 723

documented measurement needs. The analysis of the measurement barriers to technological innovation identified in these roadmaps is described in Appendix C, Technology Roadmap Review. Roadmap measurement needs in this chapter, referred to as RMNs, are summarized there.

The second method utilized the case-study approach and format for documenting measurement needs as described in chapter 4. These case-study measurement needs were gathered through industry workshops, NIST analyses of industry reports and interviews of industry representatives, and voluntary submissions by trade organizations during the period from the fall of 2005 to the spring of 2006. This methodology yielded 337 of the 723 documented measurement needs. The entire set of case-study measurement needs, referred to as MNs in this chapter, is provided in Appendix B.

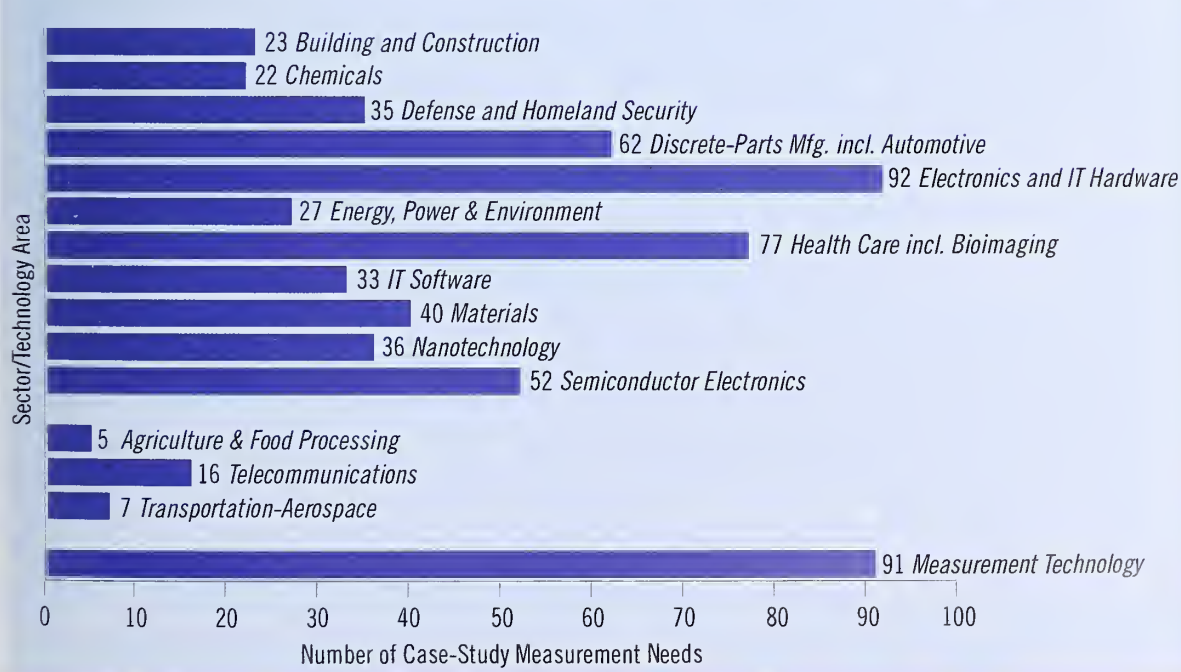
Figure 5.1
Measurement Needs by Type and Source

	Measurement Needs	Measurement Needs Documented by Industry	Measurement Needs Documented by NIST
Case Studies	337 (47%)	93 (13%)	244 (34%)
Technology Roadmaps	386 (53%)	386 (53%)	0 (0%)
Total	**723 (100%)**	**479 (66%)**	**244 (34%)**

Figure 5.1 shows the number of measurement needs by type and source of documentation. The two types of documentation are case study and technology roadmap. The two sources of documentation are industry and NIST. As indicated by the table, nearly two-thirds of the measurement needs identified in this assessment as impediments to technological innovation are documented by industry.

Figure 5.2 shows the distribution of the 337 case-study measurement needs categorized by sector/technology area. Because some of these measurement needs were common to two or three sector/technology areas, they were placed in more than one category.

Figure 5.2 Distribution of Case-Study Measurement Needs Across Sector/Technology Areas



The measurement needs in the top grouping of 11 sector/technology areas shown in Figure 5.2 have been statistically analyzed (See Appendix H). This grouping includes two of the three industrial sectors that were singled out for examination at the beginning of the assessment—specifically Semiconductor Electronics and IT Software for Information Technology. The third industrial sector, Automotive, was grouped with Discrete-Parts Manufacturing on the basis of the similarity of product and process technologies.

The measurement needs in the middle grouping in Figure 5.2—the three sector/technology areas, Agriculture and Food Processing, Telecommunications, and Transportation-Aerospace—were not analyzed because the small numbers of MNs collected for each was insufficient for identifying trends, common obstacles, and industry-wide priorities. However, this should not be interpreted as an indication that these sectors do not confront significant measurement challenges. Reviewing the summaries of specific measurement needs listed for each sector in Appendix B provides a basic understanding of some the measurement problems identified through this initial data-gathering effort.

Across the sampling of sector/technology areas chosen for this assessment, the need for new measurement technology (for example, new or significantly better test methods, instruments, or controls) is a transcending requirement, as indicated at the bottom of Figure 5.2. Ninety-one MNs cite new technology as a necessity in overcoming measurement barriers. When considering approaches to ensuring that U.S. industry remains among the leaders in the development of advanced technology, this statistic strongly suggests that attention must be directed at innovation leading to advanced measurement capabilities. However, the 91 measurement-technology MNs were not analyzed separately.

Suppliers of measurement technology are not organized in a single industry with a common set of R&D interests and objectives. Instead, they tend to be dispersed across sectors. There is no industry roadmap for measurement technology.

Overall, Figure 5.2 suggests that the measurement needs documented for this assessment, while a small sample, are indicative of measurement-related barriers to innovation confronting a substantial portion of the entire U.S. industrial economy.

Findings About Measurement Problems by Sector/Technology Area

This section contains a collection of high-level summaries of the results from the inferential analysis process for each sector/technology area. Each summary conveys the following information:

- a brief description of the industrial sector or technology area
- the technological innovations that would benefit from solutions to the measurement needs in the area
- the number of case-study and roadmap measurement needs associated with the sector/technology area
- authenticated findings and other observations (statements of potentially significant measurement issues that do not meet the standard of a finding)

Extended summaries of the results of the inferential analysis process are provided in Appendix I.

Building and Construction

Building and Construction is a $1.4 trillion industry (2005), employing 10 million people in 1 million companies throughout the United States. The construction industry is a key component of the U.S. economy and vital to its continued growth. Investment in plant and facilities, in the form of construction activity, provides the basis for the manufacture of products and the delivery of services. Investment in infrastructure promotes the smooth flow of goods and services and the movement of individuals. Investment in housing accommodates new households and allows existing households to expand or improve their housing. Construction activities affect nearly every aspect of the U.S. economy. *Building and Construction* is driven, more than any other industry, by codes and standards.

Technological Innovations at Stake

Technological innovations in *Building and Construction* that would benefit from solutions to the measurement problems cited in this assessment include the following:

- building materials, components, equipment, and structures that enhance fire safety, durability, energy efficiency, and indoor air quality
- distributed energy systems utilizing fuel cells and/or photovoltaics
- automation and interoperability of construction software, tools, and processes
- enhanced fire detection and suppression systems that integrate traditional sensors, video detection, and intelligent signal processing
- energy-efficient LED lighting in building applications
- advanced sensors/building automation systems to optimize building operations

Measurement Needs

The set of measurement needs that serves as the sample for this sector/technology area consisted of 23 MNs and 18 RMNs, the latter from 10 roadmaps.

Findings

- The integration of various systems within a building is needed in order to minimize life-cycle costs while ensuring a safe environment. Building systems integration requires real-time measurements of numerous parameters and increased collaboration among measurement solution providers in the *Building and Construction* sector/technology area.
- The lack of reliable and unbiased performance data slows the adoption of new and innovative technologies in the *Building and Construction* sector/technology area. Standard test methods are needed to capture desired performance data. Joint efforts by SDOs and the private and public sectors to develop standard test methods can ensure that unbiased performance measures are in place in a timely manner.
- The lack of validated models and data are identified as significant barriers to technological innovation in the *Building and Construction* sector/technology area. Models and performance data are playing an increasingly important role in supporting applications of innovative technology as the sector shifts toward greater reliance on performance-based standards.
- More than any other sector/technology area in this assessment, regulations are a major driver of measurement needs. Building and fire code officials, operating at the state and local levels, require proof that innovative products proposed for installation meet health and safety requirements outlined in code documents.

Chemicals

The *Chemicals* sector/technology area includes the manufacture of chemicals, biological processing of chemicals and materials, and continuous manufacturing of fluids. *Pharmaceuticals* is included in *Health Care* for this assessment. The use of chemicals impacts nearly every sector of the U.S. and world economies. The United States is the number-one producer of chemistry products in the world, accounting for 23 percent of total world chemicals production. This sector/technology area generates $550 billion a year (2005), produces more than 70,000 products, and directly employs nearly 900,000 people. It is the nation's largest exporting sector, with $109.3 billion in exports that account for 10 cents of each dollar of U.S. exports. This sector/technology area is a large energy user, consuming approximately 7 percent (1999) of total U.S. output. It also is capital-intensive and heavily regulated.

Technological Innovations at Stake

Technological innovations in *Chemicals* that would benefit from solutions to the measurement problems cited in this assessment include the following:

- advances in process-control capabilities that include innovations to process simulation for both existing and new chemical processes and in-line sensing of process conditions and parameters
- shifting of raw material sources from a primarily petroleum base to a much more mixed base that, significantly, includes biologically derived sources
- utilization of nanotechnology for advancing chemical and bio-chemical manufacturing
- measurement and characterization tools and standards supporting improved understanding of molecular structure-function relationships

Measurement Needs

The set of measurement needs that serves as the sample for this sector/technology area consisted of 22 MNs and 27 RMNs, the latter from 14 technology roadmaps.

Findings

- New thermodynamic and chemical reaction data are needed to simulate advanced chemical and biochemical processes.
- New sensor technologies for in-line, real-time, and continuous monitoring of process variables in chemically aggressive environments are needed to overcome technical barriers to manufacturing process innovation.
- New measurement technologies with chemical specificity at the nanoscale, surpassing the limits of detection and sensitivity of current techniques, are needed to overcome measurement problems that pose barriers to technological innovation in nanotechnology.

Other Observations

- Regulation will drive new measurement requirements that industry must meet in the future. Recent EU regulations on hazardous substances in electrotechnical products and on in-vitro diagnostic devices show how regulation drives the need for new measurement standards for the entire supply chain that affects these ubiquitous products.

Defense and Homeland Security

The United States spends roughly $100 billion per year on homeland security in addition to that spent on defense. This includes the services of federal, state, and local law enforcement and emergency services. Nearly three million state and local first responders regularly put their lives on the line to save others and make the nation safer. For the private sector, business continuity is a critical concern—85 percent of the U.S. physical infrastructure is privately owned. Before September 11, 2001, businesses spent $55 billion annually on security. Since then, business expenditures to fight terrorism have increased dramatically.

Defense and Homeland Security technologies are categorized into two distinct areas: detection and screening, and improvements to safety and effectiveness of first responders. Additional detail on this topic can be found in the Disaster-First Responder section of Appendix G.

Technological Innovations at Stake

Technological innovations in *Defense and Homeland Security* that would benefit from solutions to the measurement problems cited in this assessment include the following:

- advanced sensors for chemical and biological agents, nuclear radiation, and explosives
- enhanced first responder clothing, locator systems, and communications
- advanced user interfaces for homeland security and first responder technology
- improved visible and infrared video surveillance
- enhanced millimeter-wave, terahertz, and hyper-spectral imaging systems
- wireless communication systems, chip-scale atomic clocks, and chemical detection

Measurement Needs

The set of measurement needs that serves as the sample for this sector/technology area consisted of 35 MNs and 31 RMNs, the latter from 6 roadmaps.

Findings

- There is a significant need for accurate and standardized methods to evaluate system performance for existing technologies under field conditions. By enhancing evaluation techniques and methods of testing for existing technologies, a number of *Defense and Homeland Security* measurement needs can be addressed.
- New measurement technologies must be developed to support development and application of emerging technologies in the *Defense and Homeland Security* sector/technology area. Measurement needs for emerging technologies are generally different than those needed for existing technologies.

Other Observations

- It is in the interest of *Defense and Homeland Security* sector/technology area developers to bring together the various technology user groups to help define commonality among measurement needs.
- Small-market demands for a portion of the *Defense and Homeland Security* technologies cited within the measurement needs may be a barrier to their development and deployment.
- The first responder community is diverse and fragmented, including firefighters, medical personnel, and law enforcement personnel. Understanding the needs of technology providers and users of first responder and homeland security technologies will be challenging.

Discrete-Parts Manufacturing

The *Discrete-Parts Manufacturing* sector, of which the automotive industry is a significant part, involves the production and assembly of materials and components, ranging in size from nanometers to hundreds of meters, into commercially available consumer and industrial products. This sector/technology area is complex, with thousands of entities organized into multilevel supply chains. Manufacturing at large is a \$1.5 trillion industry, employing 14.2 million people. The U.S. automotive manufacturing industry is a \$120 billion industry and is the third-largest manufacturing industry behind food manufacturing and computer and electronics.

Technological Innovations at Stake

Technological innovations in *Discrete-Parts Manufacturing* that would benefit from solutions to the measurement problems cited in this assessment include the following:

- realization of making the first part, and every part thereafter, correctly
- manufacture of microscale and nanoscale discrete parts
- seamless and inexpensive hardware and software interoperability
- advanced vehicle safety systems
- semiconductor production, following the International Technology Roadmap for Semiconductors projections
- manufacture of flexible electronics
- production of hydrogen fuel cells

Measurement Needs

The set of measurement needs that serves as the sample for this sector/technology area consisted of 62 MNs and 22 RMNs, the latter from 8 roadmaps.

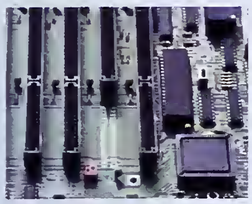
Findings

- The solution to an important class of measurement problems in manufacturing is development of new measurement technology for high-accuracy characterization of the 3D geometry of manufactured products across a spectrum of sector, technology, and application areas.
- The absence of measurement technologies for accurate in-line and real-time measurement of physical attributes of manufactured parts and assemblies, relevant to a spectrum of applications, poses a barrier to technological innovation.

Other Observations

- Physical measurements are of primary importance in this sector/technology area for control of manufacturing processes and for validation of computer simulations of new products and processes and their performance. Manufacturers need to better correlate the physically measured features and properties with the original digital specification to validate virtual models, develop standardized data sets for input into models (material data for example), and verify algorithms.

Electronics and IT Hardware



The *Electronics and IT Hardware* sector/technology area is broad and enabling. In this assessment, IT hardware includes component-level hardware, active and passive devices, systems, and end-user products. According to the International Electronics Manufacturing Initiative (iNEMI), electronics products include portable and consumer products, office and business systems, telecommunications products, medical devices, automotive products, and defense/aerospace products. The world electronics market is forecast to be worth $1.5 trillion by the year 2007 and to continue to expand at a rate faster than the world economy as a whole. Additional information on the topic of computer data storage technology can be found in Appendix G.

Technological Innovations at Stake

Technological innovations in *Electronics and IT Hardware* that would benefit from solutions to the measurement problems cited in this assessment include the following:

- IT and communications instrumentation
- fiber optics and optoelectronics
- superconducting electronics
- radio-frequency electronics
- computer data storage devices and systems
- smart sensors
- microelectromechanical systems (MEMs) and nanoscale electronic devices
- quantum computing systems

Measurement Needs

The set of measurement needs that serves as the sample for this sector/technology area consisted of 92 MNs and 19 RMNs, the latter from 7 roadmaps.

Findings

- A systems-level "measurement gap" has emerged, which impedes this sector/technology area's ability to innovate in the current environment, characterized by distributed companies collaborating to produce integrated systems.
- The measurement problems in the computer data storage area are most frequently associated with the state-of-the-art of electromechanical systems and requirements for dimensional, magnetic, and optical characterization with spatial resolutions at the nanoscale.

Other Observations

- The specialization and increased complexity of the supply chain accentuates the need for stable, widely available, standards-based measurement and test technologies.
- The achievement of the miniaturization toward which industries in the *Electronics and IT Hardware* sector/technology area are driving requires innovative nanoscale measurement capability.
- Regulatory requirements in foreign markets generate measurement problems that pose barriers to technological innovation for U.S. manufacturers who export to those markets.

Energy, Power, and Environment

The *Energy, Power, and Environment* sector/technology area covers those portions of the economy involved with the generation and distribution of energy and power, and environmental monitoring and pollution control issues. The segments included are renewable energy, electric power generation, oil and gas extraction, advanced energy utilization technologies, power distribution, and environmental monitoring. The review of technology roadmaps and case-study measurement needs for the *Energy, Power, and Environment* sector/technology area revealed specific measurement issues in diverse applications. Measurement needs relate to energy sources, including photovoltaic, fuel cells, bioenergy, wind, and fossil fuels from hard-to-access deposits. Advanced energy utilization technologies involve topics such as solid-state lighting and advanced refrigeration techniques, which currently use significant amounts of energy. Power distribution case-study topics range from electric power transmission to storage and metering of hydrogen. Environmental monitoring case-study topics range from global satellite monitoring systems to local sensors for assuring regulatory compliance.

Technological Innovations at Stake

Technological innovations in *Energy, Power, and Environment* that would benefit from solution of the measurement problems cited in this assessment include the following:

- hydrogen power
- improved methods for the distribution of electricity including the development of superconducting wires and tools for measuring power grid dynamics
- visible light emitting diodes (LEDs) for general lighting
- fusion energy through the use of tokamaks, torus-shaped devices utilizing magnetic confinement of extremely hot plasma
- photovoltaic/solar cell technologies
- new energy efficient refrigeration techniques
- high-resolution remote sensing techniques for weather forecasting, climate monitoring and finding new sources of energy
- advanced power cycles, the conversion of mechanical energy derived from combustion to electric power, for improved efficiency with lower emissions

Measurement Needs

The set of measurement needs that serves as the sample for this sector/technology area consisted of 27 MNs and 49 RMNs, the latter from 14 technology roadmaps.

Findings

- Many measurement needs associated with traditional fuel and power sources reflect extensive regulatory requirements, while emerging technology for alternative fuel and power sources reflect the anticipation of future regulation.
- In case-study measurement needs and roadmap measurement needs related to the hydrogen economy, measurement problems occur at all stages of technological innovation.

Other Observations

- The greatest concentration of measurement technology needs appear in the applied-research stage of technological innovation. Often, the measurement technology needed requires measurement innovation. Technology developers want reliable, accurate, standardized measurements before the prototype moves to the production stage.

Health Care Including Bioimaging

The United States spends close to $2 trillion per year on health care (20 percent of the U.S. economy). Autoimmune diseases (e.g., diabetes, rheumatoid arthritis, and lupus) alone affect at least 23 million people in the United States at a cost of $400 billion per year. The Department of Labor's Bureau of Labor Statistics indicates that health care is the fastest growing occupational field in the United States and predicts 33 percent growth by 2015. Technological innovations that increase capabilities or reduce costs in health care translate quickly to benefits and savings for the nation. For example, the Agency for Health Care Policy and Research reports that preventable costs total more than $20 billion per year and the electronic integration of health care information systems is projected to save $70 billion per year. *Health Care Including Bioimaging* includes bio-informatics, clinical diagnostics, and pharmaceuticals, with the major drivers for technological innovation being improved quality of life and lower cost of health services. Additional information on the topic of bioimaging technology can be found in Appendix G.

Technological Innovations at Stake

Technological innovations in *Health Care Including Bioimaging* that would benefit from solutions to the measurement problems cited in this assessment include the following:

- advanced DNA analysis using lab-on-a-chip technology
- sensor-based proteomics for early cancer detection
- new imaging modalities in MRI (magnetic resonance imaging)
- systems for lower-cost diagnosis and monitoring of bone health
- implanted devices for metered delivery of insulin
- self-assembly of soft nano-materials for bone and tissue replacement
- real-time interactive video/audio telemedicine

Measurement Needs

The set of measurement needs that serves as the sample for this sector/technology area consisted of 77 MNs and 37 RMNs, the latter generated from 9 roadmaps.

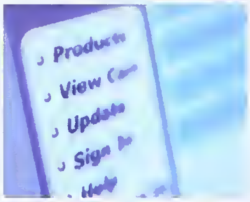
Findings

- The same measurement problem, the combination of lack of accuracy and lack of fundamental knowledge, impedes the use of new medical technologies by both clinicians and medical researchers. The potential solution, development of standards and measurement technologies provided by the public sector, is also identified for both clinicians and medical researchers.
- A solution to a principal measurement problem impeding technological innovation in *Health Care Including Bioimaging* is to be found through collaboration of industry partnerships with government laboratories and agencies focused on development and use of common standards of measurement.
- Solution of measurement problems impeding technological innovation in *Health Care Including Bioimaging* require a multi-disciplinary approach engaging specialists in, for example, chemistry, physics, materials, and computer science and engineering with those in biology and medicine.

Other Observations

- *Health Care Including Bioimaging* needs measurements and standards, such as performance standards and predictive tools, computer modeling techniques, biomarkers, and clinical trial endpoints, that deal effectively with regulatory requirements.
- Many technological innovations in *Health Care Including Bioimaging* are measurement innovations, such as new diagnostic instrumentation.

Information Technology (IT) Software



IT Software is the engine that powers a broad range of IT products and systems supporting manufacturing, finance, health care, telecommunications, transportation, defense, and most other industrial sectors. Increasingly, the U.S. and global economies rely on *IT Software* products to function effectively. The *IT Software* sector/technology area is both dynamic and diverse. In 2005, the U.S. software market grew by 3.9 percent to a value of $75.6 billion and is projected to grow at a compound annual rate of 5.8 percent during 2005-2010 to a value of $100.4 billion. Worldwide revenues for packaged software, not including software development and services, were projected at $205.7 billion in 2005 and $219.8 billion in 2006. The United States is estimated to hold approximately 50 percent of the world market. With steadily growing demands across most sectors for new software products to meet business requirements, new technological and measurement innovations will be needed to ensure software product innovations continue.

Technological Innovations at Stake

Technological innovations in *IT Software* that would benefit from solutions to the measurement problems cited in this assessment include the following:

- automated control of complex manufacturing processes
- computer-assisted diagnoses from medical images and data
- intelligent robotic systems for manufacturing, defense, and homeland security
- high-security analysis and transfer of financial and other private data
- next-generation Internet and Web services
- reliable and integrated communications among health care systems

Measurement Needs

The set of measurement needs that serves as the sample for this sector/technology area consisted of 33 MNs and 50 RMNs, the latter from 16 industry roadmaps.

Findings

- Performance measurement—in particular measurement of software and system performance, including interoperability—is critical to overcoming the measurement problems that pose technical barriers to technological innovation in the *IT Software* sector/technology area.

Other Observations

- For the *IT Software* sector/technology area, the need to improve both security and cybersecurity, themes identified as cross-cutting in the Technology Roadmap Review, presents significant technical barriers requiring measurement innovation. This becomes particularly prominent at the production, marketing, and end-use stages of technological innovation in *IT Software*.
- Issues with accuracy, data, acceptability/compatibility, and reliability, along with a lack of standards and a lack of fundamental knowledge, are measurement problems that are barriers to technological innovation, particularly during the applied research stage of technological innovation.

Materials

The *Materials* sector/technology area includes polymers, metals, ceramics, biomaterials, nanomaterials, building materials, and composites. Measurement needs span a broad spectrum of applications and issues, including primary chemical, physical, and mechanical measurands; manufacturing and processing; and application-specific function (e.g. catalysts, electronics, and building infrastructure). The measurement needs affect much of the economy and technological innovations that have a broad reach, such as those of nanotechnology and manufacturing. Highly capable, accurate, sensitive, low-cost, reliable measurement methods and instrumentation are required to realize the promise of manipulation, imaging, measuring, and modeling strategies upon which construction of complex materials and structures will be achieved.

Technological Innovations at Stake

Technological innovations in *Materials* that would benefit from solutions to the measurement problems cited in this assessment include the following:

- nanocomposite materials with increased thermal stability and reduced flammability
- high-accuracy dies for the production of sheet metal-formed automotive body parts
- better superconducting magnets for magnetic resonance imaging (MRI)
- new classes of body armor using advanced fibers
- advanced scanning probe microscopy (SPM) techniques for nanoscale mapping of chemical, mechanical, thermal, and electro-optical properties

Measurement Needs

The set of measurement needs that serves as the sample for this sector/technology area consisted of 40 MNs and 68 RMNs, the latter from 17 roadmaps.

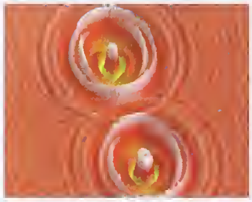
Findings

- A principal measurement problem in the *Materials* sector/technology area is the absence of measurement instruments and methods capable of accurately characterizing the behavior of complex materials systems and structures.
- In the *Materials* sector/technology area, a key factor driving the need for measurement innovation is the anticipated need to evaluate the performance and reliability of new materials successively at the production and market stages of their development.
- The timely delivery of measurement solutions in the *Materials* sector/technology area is increasingly challenged by the growing complexity of materials systems and structures and their interfaces.

Other Observations

- Significant measurement problems impeding materials technological innovations exist in the areas of accuracy, data and data collection and/or retrieval, lack of fundamental knowledge, and resolution.
- Mature *Materials* production industries face common measurement problems that impede innovations related to processes needed to improve production efficiency, in terms of cost, time, and energy.

Nanotechnology



Nanotechnology is the understanding and control of matter at dimensions of roughly 1 to 100 nanometers, where unique phenomena enable novel applications. At nanoscale dimensions, the physical, chemical, and biological properties of materials differ in fundamental and valuable ways from the properties of individual atoms and molecules or bulk matter. The National Science Foundation, in its 2001 publication, *Societal Implications of Nanoscience and Nanotechnology*, predicts that the worldwide market of nanotechnology-related products will be more than $2.5 trillion annually in 10 to 15 years. Highly capable, low-cost, and reliable measurement methods and instrumentation are required to realize the promise of manipulation, imaging, measuring, and modeling strategies upon which construction of complex nanoscale devices and machines will be achieved. Additional information on the topic of nanotechnology can be found in Appendix G.

Technological Innovations at Stake

Technological innovations in *Nanotechnology* that would benefit from solution of the measurement problems cited in this assessment include the following:

- vastly increased digital data storage capacities
- smaller, faster, more power-efficient electronic devices
- advanced drug delivery systems
- high-capacity fuel cells
- new families of high performance catalysts, sensors, and actuators

Measurement Needs

The set of measurement needs that serves as the sample for this sector/technology area consisted of 36 MNs and 49 RMNs, the latter from 10 roadmaps.

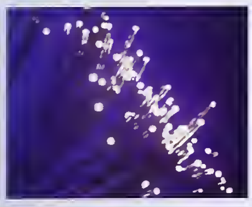
Findings

- *Nanotechnology* is unique among the sector/technology areas in its high demand for new advanced measurement instrumentation, which is needed to achieve accurate, high-resolution characterization of physical, chemical, and biological properties of materials at nanometer dimensions.
- Industry is limited not only in its ability to measure key parameters but also in its ability to identify which key parameters must be measured to meet anticipated regulations.
- The absence of measurement tools with the capability to measure properties of nanomaterials and nanodevices as they relate to functional performance and to make such measurements at speed are impediments to realization of nanotechnology products.

Other Observations

- Public-sector measurement providers that are linked to applied research sectors, production communities, market drivers, and user issues can help accelerate the innovation process.
- Innovative approaches to the measurement of nanoscale physical and chemical properties are key to technological innovation for *Nanotechnology*, especially where the fundamental limits of current measurement techniques are being approached.

Semiconductor Electronics



The *Semiconductor Electronics* industry greatly affects global economic growth. Just as its strength provides a leading indicator of the world's economic health, advanced semiconductor systems contribute substantially to new business opportunities and growth around the world. The scope of this analysis includes semiconductor memories, microprocessors, signal processors, radio-frequency and analog/mixed signal circuits, logic devices, and emerging research devices and materials. The Semiconductor Industry Association's (SIA) annual forecast of global semiconductor sales projects a compound annual growth rate of nearly 10 percent for the forecast period of 2005 through 2008 and worldwide sales of microchips from $227 billion in 2005 to $309 billion in 2008. The rapid introduction of new materials, processes, and three-dimensional (3D) structures places great demands on measurement science. The time between when new measurement techniques become available for manufacturing and when high-volume production using them begins has decreased substantially.

Technological Innovations at Stake

Technological innovations in *Semiconductor Electronics* that would benefit from solutions to the measurement problems cited in this assessment include the following:

- logic devices
- microprocessors
- computer data memories
- signal processors
- radio-frequency and analog/mixed signal circuits
- new types of semiconductor materials, devices, and systems emerging from research

Measurement Needs

The set of measurement needs that serves as the sample for this sector/technology area consisted of 52 MNs and 34 RMNs, the latter from 1 roadmap.

Findings

- In *Semiconductor Electronics* manufacturing, problems posed by the slowness of physical measurement can be overcome by greater use of computer simulations.
- New measurement instrumentation developed from pre-competitive R&D is needed to address the principal measurement problems that pose barriers to technological innovation identified in the *Semiconductor Electronics* sector/technology area.

Other Observations

- U.S. Semiconductor Electronics companies are becoming increasingly dependent on foreign providers of measurement solutions, but they must be involved in the creation of those solutions to remain at the cutting edge of technological innovation.
- High-accuracy 3D measurements in combination with simulation, visualization, and extraction of information from massive data sets will be a basis for accurate prediction of yield in high-volume manufacturing of next-generation products.

Measurement Barriers to Technological Innovation

This assessment of the USMS is based on an analysis of unresolved measurement problems that impede technological innovation. The first part of this chapter addressed those measurement problems as data. The second part of this chapter presented findings for individual sector/technology areas from an analysis of the data for the individual areas. This part of the chapter presents findings from an analysis of data for all sector/technology areas taken together and observations about measurement barriers that cut across areas.

Findings

Fundamentally new measurement technologies are required to overcome the limitations of accuracy, which are the most prevalent type of measurement barrier to technological innovation across all sector/technology areas.

Inadequate accuracy is the most frequently cited measurement problem impeding innovation within the individual sector/technology areas and in the set of all the measurement needs taken together. It is often cited in combination with inadequate resolution and in many cases with a lack of fundamental knowledge as related factors. Accuracy, resolution, and lack of fundamental knowledge as measurement barriers reflect two trends: some measurement technologies are reaching the limits of their capabilities, and/or technological advances and societal change are precipitating demand for entirely new measurement technologies. Accuracy and resolution are notably important barriers in economic sectors where technological advance is occurring most rapidly: health care, electronics (both semiconductor and non-semiconductor), information technology, telecommunications, nanotechnology, and materials.

While solutions to the issues of accuracy, resolution, and other barriers are often sector-specific, there are commonalities in measurement science that will be required to support individual solutions. More accurate measurement of chemical and biological species, for example, is important to the chemical industry as well as to the environment, health care, agriculture and food, nanotechnology, materials, and homeland security sector/technology areas. The development of entirely new measurement technologies and research to increase the fundamental knowledge base will be required in some cases to overcome some of the limitations of current methods. There is clear indication within the case-study measurement needs, verified by authenticators, that research is needed to develop new fundamental knowledge to address the measurement accuracy barrier, and that the public sector has a direct role in development of solutions to specific accuracy-related measurement problems.

The absence of accurate sensors for real-time monitoring and control of manufacturing processes and environmental conditions poses a significant barrier to innovation that spans multiple sector/technology areas.

The inability to make real-time, non-intrusive/non-destructive measurements of production and process variables is a measurement barrier in a number of economic sector/technology areas (chemicals, energy and power, basic materials such as steel, aluminum, glass, automotive, metal working). Real-time measurements are needed to inspect equipment integrity and monitor and control production for efficiency and product quality, among other factors. The capabilities of currently available sensing technology are a limiting factor in some cases. For example, measurements need to be made in harsh operating environments (high temperature, pressure, and corrosives), which requires rugged sensing and detection technology that is not readily available today. There are some common measurement barriers in production environments that could potentially be addressed through the collaborative efforts of multiple industries and organizations. In other cases, the solutions are very application specific, and small-market/low-volume demand may inhibit development by the private sector.

The absence of adequate sensors and detectors in applications related to environment, human health and safety, industrial productivity, and quality of life poses a significant measurement barrier to technological innovation for the United States. Inadequate sensing and detection capability was noted in every economic sector/technology area as a measurement barrier. The requirements for sensing and detection are diverse, ranging from the need to control manufacturing processes to the delivery of energy, detection of threats, and monitoring of environmental impacts. Despite this diversity, commonalities exist among sensing requirements. For example, the need to sense, detect, and measure the elemental constituents of gases is a requirement in chemicals manufacture; energy generation; monitoring building air quality; and detection of chemical, radiological, and biological attack. Entirely new science, materials, and technologies may be required to address these diverse sensing requirements. Unique applications of nanotechnology, biotechnology, and advanced electronics may have the potential to overcome some of these measurement barriers.

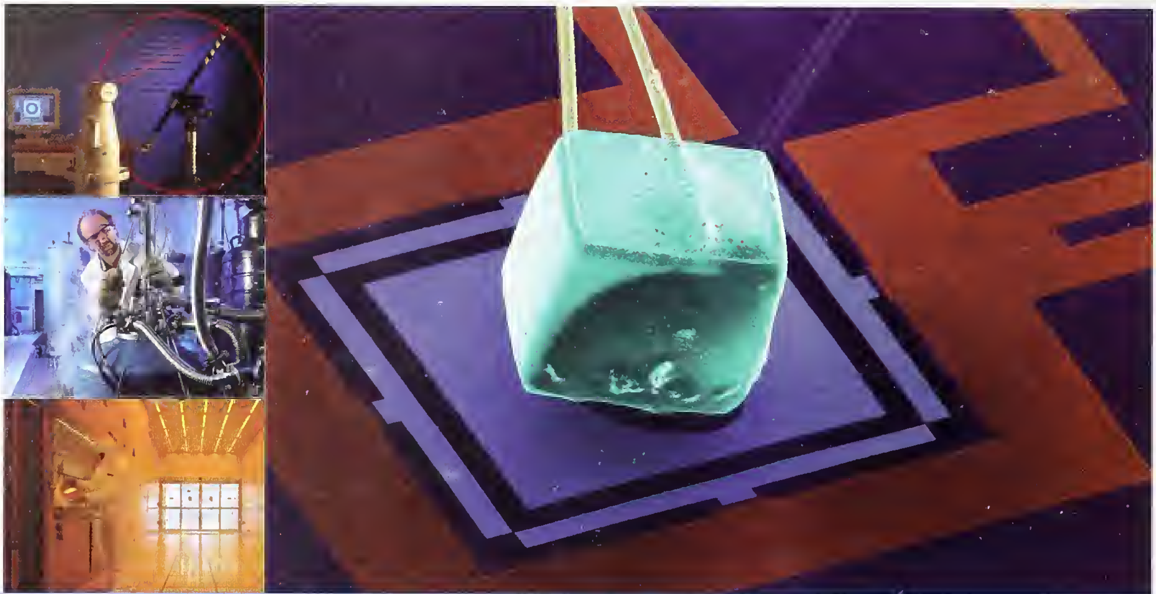
A lack of standards, benchmarks, metrics, and protocols for assessing system-level performance of new technologies, including the compatibility and interoperability of hardware and software systems, is a substantial measurement barrier in a number of sector/technology areas.

In *Building and Construction*, for example, performance benchmarks, rather than prescriptive design standards, are becoming critical as there is a need to predict and compare how innovative materials and components will perform in the final constructed product. In *Defense and Homeland Security, Health Care Including Bioimaging*, and other sector/technology areas that rely heavily on information systems, standardization and benchmarks for software and hardware system performance and interoperability are critical. Computing power has advanced so rapidly over the last decade that insufficient emphasis has been given to measuring performance in practice. Software and hardware producers are now being challenged to demonstrate and predict the performance of systems that are critical to our economy and infrastructure. Standardization of performance measures will be essential for uniform acceptance across many sectors and end users.

The fact that the need to measure system performance has been identified as a significant technical barrier to innovation in the service-like sectors of *Building and Construction, Health Care Including Bioimaging, Defense and Homeland Security*, and *IT Software* may be an indicator that the problem of measurement of system performance is a barrier to the use of new systems technologies in the service sectors of the U.S. economy overall (as well as in the manufacturing-focused sectors examined in this assessment).

Other Observations

- With the increasing importance of computational simulation tools to product design, development, and manufacturing, a limited availability of robust, validated measurement-based models is a concern for nearly every economic sector/technology area.
- For measurement problems encountered in, or anticipated for, the later stages of technological innovation (production, market, end use), standardization plays a progressively greater role in solutions to measurement problems, as do industry consortia/partnerships as solution providers.
- A lack of measurement capability to demonstrate compliance with changing regulatory requirements calls for continuous development of new measurement technology.



VI. Summary of the Assessment of the USMS

This chapter considers the USMS from a broad perspective. It reports conclusions on the structure and function of the USMS, challenges to the system's capacity to overcome measurement barriers to technological innovation, and responses needed to meet these challenges so that the nation can continue to be an innovation leader. Collectively, these conclusions represent the assessment of the USMS, as viewed from the vantage point of technological innovation.

The judgments reported here are based on the findings from the inferential analysis of measurement needs discussed in the previous chapter. The USMS-wide conclusions also draw upon recently published reports and studies dealing with science and technology, innovation, and the nation's performance in these two areas.

Distilled from the full set of 723 measurement needs documented for this study, the conclusions reported are high-level judgments that provide a system-wide perspective of the USMS. While high level and relatively general in nature, they represent a first step toward understanding and addressing system-level weaknesses that diminish the ability of the USMS to support innovation in a rapidly changing technology environment and an increasingly competitive global economy. These conclusions deal successively with the following:

- the overall structure of the USMS
- challenges to the system posed by the economic imperative for continuing technological innovation
- possible responses to those challenges

Structure and Function of the USMS

The USMS must provide a measurement infrastructure for the nation to keep pace with the measurement needs of a growing, rapidly changing, technologically sophisticated economy.

The USMS today is a complex network of diverse private- and public-sector entities that together develop and supply the products, services, and infrastructure used to carry out a variety of measurement-related tasks and responsibilities in nearly every part of the U.S. economy. As science progresses and technology advances, the USMS will continue to grow in complexity—requiring that attention be paid to the individual parts of the USMS, and to the network as a whole. Like the processes, products, and services it supports, the USMS will be challenged to

function as a coherent system. To use an information technology analogy, it must continue to efficiently serve legacy needs, such as those addressed by traditional weights and measures functions specified in the U.S. Constitution.

For example, seven percent of the case-study measurement needs analyzed in this assessment identified traditional types of measurement services—including measuring instrument calibrations, third-party verifications, and measurement-based product testing—as solutions to measurement problems that pose barriers to technological innovation.

The USMS also must respond effectively to needs for entirely new types of measurements, such as those generated by new applications of existing technology (such as telemedicine) or by new or emerging technologies (such as nanotechnology, or tissue engineering for regenerative medicine).

Novel, multidisciplinary approaches often will be required to meet new types of measurement needs, significantly extending the established USMS structure and paradigm.

Information technology continues to place new demands on the USMS—demands that require adding elements and capabilities that are outside the scope of the basic measurement infrastructure common to most industrialized nations. Software applications, now deeply embedded within the economy and still growing in variety and capability, necessitate measurements unlike those supported by the SI.

The diversity and complexity of the USMS is both a strength and a challenge to development of coherent responses to the measurement barriers impeding innovation in the United States. For example, providers of measurement solutions include the more than 450 U.S. private-sector standards-developing organizations and the thousands of U.S. businesses providing measurement instruments, materials, components, and analytical software. Foreign businesses also are measurement-solution providers.

Many conventional providers of measurement solutions will be called upon to address new measurement needs. Lack of standards, for example, was noted as an impediment to technological innovation in nearly every economic sector covered in the technology roadmaps. Among the case-study measurement needs, 22 percent identified new standards, reference materials, and reference data as potential solutions.

The USMS must evolve in concert with the international measurement system to enable U.S. companies, including technology innovators, to meet the growing number of measurement-based standards that influence access to and transactional efficiency in the global marketplace.

The Organization for Economic Cooperation and Development has estimated that 80 percent of world trade is influenced by standards or by regulations that embody standards. Measurement-related requirements are essential components of most of these standards and regulations. Examples include product testing and other conformity assessment requirements, quality and compatibility standards, measurement traceability requirements, and performance specifications.

If USMS solution providers, products, and services are recognized internationally, U.S. exports will encounter fewer technical barriers that can impede access to international markets and add to the cost of doing business. This recognition also translates into greater efficiency in global supply chains and into greater trust in customer-supplier transactions.

Since measurement-related requirements are integral components of standards, leadership in measurement capabilities often can be leveraged for competitive advantage. Developing advanced test and measurement methods and including these in international standards can ease the access of U.S. technology to global markets. They also can simplify steps to demonstrate compliance with standards and regulations.

International recognition of U.S. measurement methods and tools can pave the way for exports of U.S. measurement equipment and services. Therefore, U.S. suppliers of measurement solutions must stay abreast of measurement needs worldwide, track advances and prospective improvements in other nations' measurement technology, and regularly assess and forecast what measurement capabilities will be required to support the competitiveness of U.S. companies and their technologies in the international marketplace.

Challenges to the USMS Posed by Technological Innovation

Measurement innovation (breakthroughs in measurement capabilities) often will be a critical determinant of successful technological innovation in nearly all sectors of the economy.

As indicated by technology roadmaps and case studies reviewed for this assessment, nearly every industry experiences measurement needs directly tied to its innovation performance. In terms of number and variety, these needs clearly indicate that the USMS continues to have a vitally important function in our economy.

The magnitude of the challenges to the USMS posed by these needs varies with the types of new technologies being pursued. Incremental advances in existing technologies may require only incremental advances in today's measurement-related products and services. So-called breakthrough technologies—which range from quantum computing to a hydrogen-powered transportation system to systems of nanoscale devices—will require entirely new types of measurement capabilities. In other words, realization of revolutionary technologies will typically necessitate corresponding levels of innovation in measurement technology, beginning with goal-driven fundamental research. As illustrated by the International Technology Roadmap for Semiconductors, lack of research and development directly addressing key measurement problems with no foreseeable solutions from today's vantage point is flagged as a "show stopper"—an unmet technical need significant enough to prevent the attainment of next-generation technology goals.

The USMS must anticipate and deliver innovations required to meet measurement needs of producers and users of new technology in the manufacturing sector, as well as users of new technology in the service sector.

Measurement innovations that are breakthroughs in measurement capability will be a critical determinant of successful technological innovation in nearly all sectors of the economy.[8]

Recognition of the need for measurement innovation extends well beyond the semiconductor industry. Of the 164 industry technology roadmaps reviewed for this assessment, 82 percent identified measurement problems that pose barriers to technological innovation. For example, development of performance standards and benchmarks for systems and components affects a diverse set of usage areas—from software to smart control systems for buildings.

The utility and value of solutions to these measurement needs will not be confined to the businesses or industries that develop and market new technologies. Users of the technologies also will benefit significantly. Successful applications of the new technologies may hinge on innovations in measurement capability. For example, a variety of sectors are looking at radio frequency identification (RFID) technology in a variety of new uses, from wholesale and retail examples to application in defense and homeland security. Still-to-be-resolved measurement problems for no-line-of-sight RFID technology include issues related to standards for hardware and software, interoperability within limits of frequency and transmission power, and privacy/security.[9]

To achieve the promise of nanotechnology—an area that may yield the most important technological innovations of the first quarter of the 21st century—major innovations in measurement science and measurement technology are required.

Nanotechnology—perhaps the most economically important area for technological innovation in this and the coming decade—is confronted by measurement barriers that require breakthrough innovations in measurement capabilities.

Successful technological innovation ultimately hinges on the availability of advanced measurement capabilities that are production ready. Worldwide, the market for nanotechnology products has been projected to exceed $2.5 trillion within 10 years. Innovations from nanotechnology are being pursued around the globe. Total government spending on nanotechnology R&D was more than $4.6 billion in 2005, including the U.S. investment of more than $1.7 billion. The global investment—private and public—exceeded $9.1 billion.

Nanotechnology products derive new functionalities and increased performance from phenomena that are manifested only in matter of nanoscale dimensions. These phenomena are the subject of intense scientific research, where basic discoveries in nanoscience are being made, and in the application of the nanoscience, where the foundation for commercialization of nanotechnology products is laid. The ability to apply nanoscience and to develop nanotechnology products depends on the ability to measure the behavior of matter at the nanoscale and to characterize nanoscale materials, structures, and devices.

Nanotechnology stands out in this assessment in terms of the acuteness of need for new fundamental measurement science and technology to overcome the measurement barriers to technological innovations based on advances in this rapidly emerging area. There are major measurement barriers that impede the ability to characterize virtually every property and attribute of nanomaterials, devices, and structures and the ability to understand the link between properties and functionality. The fundamental nature and diversity of measurement problems that are impeding nanotechnology call for entirely new families of advanced measurement instrumentation. Compared with solutions identified for all sector/technology areas in this assessment, the need for new measurement instruments was cited twice as often for nanotechnology. Meeting this need will require new measurement science and new measurement technology.

Successful technological innovation ultimately hinges on the timely availability of production-ready, advanced measurement capabilities.

To a large extent, measurement and analytical capabilities set the pace of technological progress and dictate how rapidly the benefits of that progress reach the marketplace, where they can be enjoyed by society. New and better measurement tools are needed to sustain advances and discoveries in the laboratory. These tools can help distinguish artifact from novel phenomenon, for example, and enable replication and verification of research results across laboratories. Without such tools, science will not acquire detailed knowledge of the exotic properties and the novel behavior of matter at the nanoscale, which, in turn, is needed to advance the pursuit of the principles and laws that govern molecule-sized materials and structures.

Ultimately, however, our nation's ability to attain the full promise of nanotechnology and other anticipated revolutionary technologies will require production-ready measurement tools. In the industry technology roadmaps reviewed, needs for production-level measurement capabilities were cited widely as barriers to technological innovation. Measurements that are technically feasible in the highly controlled environment of a research laboratory often are not viable in production environments without considerable additional effort and resources.

To manufacture the multitude of nanotechnology products that are envisioned, U.S. industry will require measurement tools with new capabilities and characteristics. These tools must span the continuum from nanometers to micrometers to millimeters, be configurable in array formats, achieve high throughputs, and provide real-time information delivery. These new measurement tools must not require highly specialized

environmental conditions for satisfactory operation. Further, they must meet these requirements while being affordable and versatile.

When market drivers and potential economies of scale exist and returns on research investment can be captured, the private sector often steps in to develop measurement systems for production-level applications. In some cases, however, measurement needs may go unaddressed because returns on research and development efforts cannot be captured by individual firms—the so-called non-appropriability problem common to generic technologies. Such consequences can result in less-than-optimal productivity, lower product quality, and the inability to predict performance and functionality—all of which can translate into competitive disadvantages for the nation. To bolster technological innovation and foster U.S. leadership in global markets, public and private investment in cutting-edge measurement science, standards, and technology that the private sector ultimately converts to production-level measurement technology will be essential.

The inability to adequately measure system performance (especially the performance of software and information technology hardware) limits the effectiveness and application of new technologies in important service industries.[10]

Solving issues of system-performance measurement in information technology applications is a significant challenge for the USMS, given the diversity and sensitivity of some applications and the absence of foundational measurement science for such metrics.

To an ever-increasing degree, the U.S. economy relies on information technology in its many manifestations and diverse applications. As the speed and power of hardware increases and as the functionality of software deepens and expands, numerous forms of information (and communication) technology are combined and configured into networked systems of tremendous complexity—often on an *ad hoc* basis.

This assessment has identified the inability to reliably measure the performance of complex systems to be a significant barrier to technological and organizational innovation in manufacturing and service industries that rely heavily on information technology.

More than 70 percent of case-study measurement needs identified in the IT software sector pertain to issues regarding the measurement of software and hardware performance and reliability. Reviews of industry technology roadmaps also indicate that system performance measures are high-priority needs in IT software and represent important issues for user industries and groups, such as building and construction, health care, emergency first responders, homeland security, defense, finance, and retail. These and other sectors rely on the exchange of volumes of information.

Virtually every business in the United States now depends on software for development, production, distribution, and after-sales support of products and services. Innovations in such fields as robotics, nanotechnology, and biotechnology and genetic research have been enabled, in large part, by low-cost computational and control capabilities accomplished through software applications. However, annual costs due to software errors and failures, which could be reduced with an adequate testing and measurement infrastructure, run into the tens of billions of dollars.

New measurement capabilities are required to support emerging technologies for sensing and controlling a wide array of properties and parameters in applications critical to industrial competitiveness as well as to national security and human health and safety.

Technology roadmaps and published reports indicate that the need for new, more powerful sensor technology is pervasive throughout the economy. The USMS has historically been a leader in the development of sensors—a measurement technology in its own right—and supporting measurement tools and services. Today, technology is advancing to meet more demanding sensing requirements in a variety of areas, including biometrics, micro- and nano-electromechanical systems, and smart, wireless communications networks. However, in some cases, today's technologies are operating at or close to their limits

or their requirements are exceeding current capabilities. Development of next-generation sensors and sensor networks will require fundamentally new approaches, including innovations in complementary measurement technology.

Because sensors are pervasive to the economy, breakthroughs in sensing technology could have huge economic impacts. For example, wide-area measurement systems are needed to effectively control the next-generation electricity transmission grid. These systems also will be important for future remote monitoring of global carbon emissions and climate change. For homeland security, entirely new sensing technologies are needed to detect biological, radiological, and chemical agents, and to more accurately monitor the safety of the food and water supplies.

Given the pervasiveness and diversity of anticipated sensor applications, the USMS is challenged to provide measurement tools necessary to achieve the more exacting detection and control requirements envisioned.[11]

Technological innovation has in some cases been stalled due to the lack of measurement technology to assure and verify compliance or to resolve questions regarding potential risks and hazards that emerging technologies may pose.

Accurate, reliable measurements are essential for assuring compliance with a wide range of regulations implemented to protect human health or the environment, assure safety, or accomplish other societal goals. Sometimes demonstrating regulatory compliance can be difficult. Regulation was found to drive measurement needs in 70 percent of the industrial sectors in the review of technology roadmaps. Product areas/industries that are affected include food, drugs, power generation, transport systems, telecommunications, and buildings. In some industries, regulations primarily impact not products, but the effluents or wastes from industrial processing.

In all sectors, regulations were found to have an impact on technological innovation, sometimes by inhibiting the movement of products into the marketplace and, in other cases, by impacting how products are manufactured or constructed. For example, in the health care sector, new medical devices that have the potential to provide dramatic improvement over conventional diagnostic tools may be slow to market because the available measurement technology is insufficient to demonstrate safe performance.

In nanotechnology, lack of common measurement tools, protocols, and standards for characterizing emerging nanomaterials and conducting analyses to identify any environmental or health effects is prolonging uncertainties about the safety of the novel materials. Until these issues are resolved, the development and introduction of potentially revolutionary nanotechnology products will likely be delayed.

Responding to USMS Challenges

Pre-competitive, collaborative R&D is an effective vehicle for addressing needs for new measurement technologies, many of which will have broad utility.

Fundamental measurement problems pose major obstacles to technological innovation. The technology roadmaps and case studies reviewed during this assessment indicate that industry often agrees on shared measurement needs. In contrast, companies are reluctant to discuss measurement needs specific to their products, operations, and near-term technology goals because communicating this information can expose their organizations to competitive risks. Not surprisingly, technology roadmaps identify common, or generic, measurement needs that can be resolved primarily through pre-competitive or public domain activities. Analysis of the case-study measurement needs leads to a similar finding.

Federal research organizations and other public-sector organizations that are part of the USMS will be challenged to prioritize needs within a growing inventory of measurement-related obstacles to technological innovation.

Because the knowledge and early-stage solutions generated by pre-competitive R&D are nonproprietary and widely disseminated, the public sector can play a significant role in responding to these needs. For more than 60 percent of the

case-study measurement needs, public-sector organizations (academia and government agencies and laboratories) were cited as having a key role in efforts to resolve pre-competitive measurement problems that impede technological innovation. Obviously, budget constraints, organizational priorities, and other factors dictate how measurement needs are prioritized and addressed within public agencies and laboratories. This will require collaborative development of criteria for prioritizing measurement needs and R&D directions, consistent with other federal research priorities.

USMS stakeholders, particularly supporters of fundamental research, need to strengthen the two-way link between advanced measurement capability and the scientific discoveries that become the basis for future technologies.

Major advances in measurement science and, ultimately, measurement capabilities, begin with fundamental knowledge acquired through basic research, while progress in measurement science enables more productive research, facilitates confirmation and exchange of results, and leads to new rounds of discovery.

Developers of new product technologies draw on a rich pool of scientific knowledge, produced both nationally and internationally. Advances in metrology, or measurement science, also are products of this pool. At the same time, progress in measurement science leads to new understanding and new measurement capabilities, including instrumentation, that researchers use to broaden and deepen the knowledge pool.[12] As one writer characterized the relationship, metrology is the "subdivision of science that underlies and assists all others."[13]

Solutions to one in four of the measurement problems identified in technology roadmaps require fundamental advances in knowledge, acquired through basic scientific research. The range of inquiry reaches from quantum physics to the kinetics of chemical reactions and the dynamics of interactions between proteins and cell membranes. The results of fundamental investigations may be the seeds of future technological innovations that become the "next big thing" in economic sectors as diverse as energy, aerospace, and health care, and include fundamental physics in microgravity environments to allow study in space. These examples only begin to touch on the science needed to bridge the gap between critical measurement needs and effective solutions that enable new rounds of discovery. These measurement solutions become embedded facilities, instruments, and equipment needed for leading-edge research and technological development.[14]

The measurement barriers to technological innovation identified in this assessment of the USMS suggest that concerted and coordinated effort by the private and public sectors will be necessary to achieve timely resolution.

The industry measurement problems documented in this assessment represent shared technical challenges that industry is willing to identify publicly. For most of these measurement needs, industry has identified public-sector institutions as potential solution providers. Because of the complexity, pervasiveness, and systems nature of many of the measurement barriers, no organization can afford to undertake them alone, especially since returns on measurement solutions often are not easily captured by the innovators. In fact, the characterization and analysis of industry-identified measurement needs conducted as part of this assessment suggest that even sizable industries are unwilling or unable to tackle those measurement barriers on their own.

In addition, the data suggest that involvement of industry consortia and private-public partnerships can be a key strategy for attacking measurement barriers to innovation that occur at the

very early, pre-competitive stages of technological innovation. In some cases, the public sector—NIST, as the nation's measurement institute, as well as government agencies and laboratories and academia—may play a lead role. Since U.S. industry operates in a global economy, U.S. organizations also might cooperate with foreign and international organizations to develop generic solutions to widely recognized measurement problems.

Conclusion

This assessment concludes that the USMS, as constituted today, is meeting the basic requirements of an effective national measurement system: that is, it provides the measurement infrastructure—measuring instrument calibrations, third-party verifications, and measurement-based product testing—necessary to assure uniformity of measurements supporting commercial transactions vital to the U.S. economy. However, demands on the system associated with increasingly rapid technological change, coupled with technology convergence, continue to grow in number and complexity. These demands necessitate the enhancement of elements and capabilities that are outside the scope of the basic measurement infrastructure that lies at the heart of the USMS. And they challenge the USMS as it is currently structured. The diverse and complex USMS has many strengths, but also faces formidable challenges with respect to enabling and promoting technological innovation.

The measurement-needs data, findings, and conclusions of this assessment are substantial evidence of the considerable extent to which measurements, measurement science, and measurement technology impact technological innovation. This is clear even though the USMS assessment covers only certain sectors, technologies, and disciplines. Unresolved measurement problems pose substantial barriers to innovation.

This assessment clearly shows that measurement barriers impede technological innovation in many of the manufacturing sectors of the economy, including chemicals, electronics, materials, and discrete-parts manufacturing. It also shows that such barriers impede innovation in a number of service sectors, including building and construction, health care, and homeland security. The results suggest that measurement barriers impede innovation across virtually all sectors of the economy.

The challenges identified in this assessment indicate the need for the principal institutions of the USMS to enhance cooperation in addressing critical measurement needs to accelerate technological innovation.

The great extent to which measurement problems can impede innovation across sectors and technologies and the priorities placed on measurement needs by industry provoke cautionary thoughts for the future. The United States as a nation and the USMS as an element of the nation's innovation infrastructure must act now to overcome measurement barriers of the type identified by this assessment. Otherwise, the nation will be challenged to maintain its position as a global leader.

VII. Next Steps

Unresolved measurement barriers impede technological innovation, the primary driver of the nation's economic and productivity growth and the key source of competitive advantage in the global economy. Overcoming these barriers is essential if the United States is to continue to be the global leader in developing and commercializing new technologies.

To meet the changing requirements of our economy and to respond rapidly to technical challenges, the USMS must become a more agile and versatile system, capable of sustaining technological innovation at a world-leading pace. Improving the effectiveness of the USMS requires both immediate action and a strategic, long-term approach.

This assessment has identified seven actions to be taken as next steps to enhance USMS capabilities and to accelerate technological innovation. These steps are recommended for consideration and action by all USMS stakeholders, acting individually and in collaboration.

NIST, in its unique role as the nation's national measurement institute, has committed to participate in each of the seven recommended actions.

Promote awareness of the critical measurement needs identified in this assessment throughout the measurement research community.

The measurement research community is a key contributor to measurement solutions at every stage of technological innovation. However, the contributions of measurement research, embedded in the nation's technological infrastructure, are often invisible to decision makers in industry and government. NIST will widely distribute this assessment to the measurement research community in both the private and public sectors, communicate the importance of the findings and conclusions, and encourage decision makers to address these critical needs. Potential partners in building mutual awareness of industry measurement needs and measurement research community capabilities include industry consortia, producers of industry technology roadmaps, trade and professional organizations, performers of scientific research, and the National Science Foundation and other sponsors of research.

Identify strategies to bolster the effectiveness of USMS solution providers and accelerate development and delivery of measurement technologies that respond to measurement problems impeding innovation.

USMS measurement solution providers are widely dispersed in both the private and public sectors. This fact complicates efforts to communicate needs and opportunities, which can slow the development and commercialization of new measurement technologies. There currently exists no formalized measurement technology industrial sector, and most current technology roadmapping efforts do not explicitly address measurement needs at a detailed level.

NIST will reach out to groups of measurement solution providers and technology innovators to create a dialogue about how to improve the efficiency and effectiveness of the USMS in supporting technological innovation. This effort will embrace both the private and public sectors, with the goal of proposing mechanisms for improving the USMS that can be sustained over time. These mechanisms could include collaboration tools, such as communication networks and new information resources.

Foster collaboration to accelerate measurement breakthroughs.

Today's science and technology challenges require ever more accurate and reliable measurement tools and associated services. As a result, developing effective partnerships across disciplines and organizations is becoming increasingly important. Many case studies in this assessment identified industry consortia/partnerships and interagency government partnerships as essential to overcoming measurement barriers. Collaborative arrangements can foster innovative results. However, effective collaboration may demand new mechanisms. NIST will explore methods to promote USMS collaborations that address specific industry and national goals. Given the breadth and diversity of measurement needs, a variety of collaborative approaches will be considered, including government interagency groups, industry-government consortia, industry-wide alliances, international forums, and Internet-based vehicles for information exchange.

Encourage industrial sectors to identify and prioritize measurement needs.

Measurement needs identified in the roadmaps and case studies reviewed, as well as any measurement needs identified subsequently, should be prioritized by the industrial sectors they affect. Criteria to guide and facilitate setting priorities should be established. Measurement solution providers and other experts (as appropriate) should participate in the prioritization process to ensure that industry's requirements are accurately understood and that the time frames for expected results from measurement R&D are realistic. Priorities and time frames should be updated regularly and communicated to solution providers and prospective users. For the longer term, more active involvement of the measurement community with technological innovators in general and roadmap developers in particular will help ensure that needs are promptly addressed.

Facilitate pursuit of solutions to the specific industry measurement problems documented in this assessment.

The measurement needs that form the basis of this assessment of the USMS are real, unresolved measurement problems for which industry is seeking solutions. The case-study measurement needs have been documented specifically for this assessment and describe in detail the measurement problems and potential solutions. The roadmap measurement needs have been abstracted from industry technology roadmaps where, in general, they are described in broad terms. NIST will facilitate pursuit of solutions to the measurement needs accordingly.

For roadmap measurement needs, NIST will communicate its report to technology roadmap developers to begin a dialogue in pursuit of solutions. For case-study measurement needs, NIST will communicate with potential solution providers.

Identify shared measurement needs and opportunities for synergy across industries and research areas.

The USMS has a diverse range of solution providers that serve an even broader diversity of customers. Once individual industrial sectors determine priority measurement requirements, cross-sector action plans should be developed, where appropriate. Some priorities will be addressed by short-term R&D (one to three years), while others will require fundamental research over a longer period. Many short-term measurement needs, once communicated clearly, likely will be addressed by private-sector efforts. Fundamental measurement research and pre-competitive R&D needed to address longer-term needs may require government funding and coordination.

Cross-sector action plans can become an informative part of the USMS infrastructure and help guide planning activities in both the private and public sectors. As a result, stakeholders and researchers can pursue measurement solutions collaboratively, leveraging R&D resources.

Foster strategic public-sector investments in measurement R&D to accelerate technological innovation.

Leading-edge technology development continually demands new and better measurement capabilities. Measurement needs documented as case studies in this assessment identify roles for both the public and private sectors as providers of measurement solutions to the measurement barriers confronted. A potential public-sector contribution to such solutions is strategic investment in both cutting-edge research that focuses on discoveries in measurement science and in the tools of science—facilities and instruments that enable discovery and development—particularly unique, expensive, or large-scale tools beyond the means of a single organization. NIST's unique roles in such solutions are conducting fundamental measurement-related research, developing tools to measure, evaluate, and standardize, and partnering with industry to transfer these tools to the private sector. Given this infrastructural focus, NIST is positioned to foster the strategic public-sector investments outlined here. In turn, private-sector investments enable the translation of fundamental discoveries into the production of useful and marketable measurement technologies, processes, and techniques.

Given the diversity of government-funded research, each funding agency will need to act individually to identify and support measurement R&D targeted to spur technological innovation within their mission-related areas of responsibility. These areas include defense, homeland security, health, space, energy, and environmental protection. However, this assessment points to several areas where cross-agency efforts to address broad measurement problems would enhance effectiveness.

Below, specific activities are suggested to support strategic use of public-sector investments in measurement-related R&D to accelerate technological innovation.

- *Keep end users and potential solution providers informed of federal measurement capabilities*:
  Resources and capabilities of the USMS, including those of—or funded by—the federal government, are extensive. NIST will explore and promote approaches by which federal agencies can inform the measurement R&D community in general, and potential solution providers in particular, of specialized measurement-related instruments and facilities accessible to outside users.

- *Incorporate insights from this assessment into strategic and program plans:*
  NIST will make the results of this assessment available to other government agencies for consideration during their strategic and program planning. The needs and findings reported in this assessment may serve as a resource to help agencies identify opportunities to address measurement priorities corresponding to their mission-related interests. For its part, NIST will incorporate the results of this assessment into its strategic and program plans. As part of this process, NIST will evaluate approaches to accelerate measurement innovation in economically important areas. These might include new criteria for project selection, realignment of NIST-wide priorities, new partnerships, and increased bilateral, regional, and international collaboration. A key element of NIST plans will include working collaboratively with SDOs to proactively identify measurement-related priorities to support standards development in nanotechnology and other emerging technology areas. NIST also will identify and evaluate new approaches to enable performance-based standards, protocols, benchmarks, and metrics.

- *Establish an explicit agenda for measurement innovation:*
  The core purpose of a measurement innovation agenda would be to identify opportunities for synergy in federally supported R&D to eliminate measurement barriers to technological innovations. Input from the private sector on this matter will be sought. One possible vehicle for developing such an agenda would be a new interagency task force on measurement science and technology. This task force would be charged with establishing a cohesive, proactive process for identifying national measurement-related priorities as well as opportunities for improving USMS capabilities in support of innovation.

Conclusion

This assessment underscores the importance of measurement advances to U.S. competitiveness in global markets. Many of the measurement solutions identified for the individual sector/technology areas, as well as solutions that apply across several sector/technology areas, possess the potential to benefit many sectors of the economy, including sectors beyond those examined in this assessment.

The focus of this assessment on technology as represented by physical devices, materials, or systems, results in an emphasis on manufacturing sectors rather than on service sectors. Reviews of measurement needs in three areas—*Building and Construction, Health Care,* and *First Responders*—did, however, provide an indication of needs in the service sectors.

Feedback on this assessment from stakeholders in industry and government will be solicited and used to improve and guide the next steps described above. Ultimately, the success of the USMS improvement effort will depend on the participation of many different types of organizations in the United States and abroad. Efforts that are both concerted and collaborative will enable the efficient and effective use of private and public resources to resolve measurement problems that limit technological innovation.

Global leadership in science and technology depends on our ability to develop innovative measurement technology.

Glossary of Terms and Abbreviations

A

ANSI: American National Standards Institute; a federation of SDOs, companies, trade associations, government agencies, and consumer groups.

APMP: Asia Pacific Metrology Program.

Authentication: The term used in this report to indicate the process of validation of measurement needs and findings by representatives of U.S. industry.

B

BIPM: International Bureau of Weights and Measures.

C

Case-Study Measurement Needs: One-page, standalone summaries of industry measurement needs.

CIPM: International Committee for Weights and Measures.

Conclusions: Judgments about the capacity of the USMS to address the identified measurement barriers to technological innovation.

D

Declarative statements: The term used in this report to indicate factual statements based on a sufficient number of documented measurement needs and supported by sufficient fact and logic to qualify as potential findings.

F

Findings: The term used in this report to indicate factual statements about measurement problems that pose technical barriers to technological innovation that have been authenticated.

G

GPS: Global Positioning System.

I

ILAC: International Laboratory Accreditation Cooperation.

Inferential analysis process: The term used in this report for the process used to generate findings and conclusions.

IEC: International Electrotechnical Commission, an organization that develops standards on electrical, electronic, and related technologies.

ISO: International Organization for Standardization, a body that includes the national standards bodies of 149 countries and develops and adopts international standards for nearly every industry sector.

ITU: International Telecommunications Union, an organization that develops standards for information and communications technologies.

M

Measurand: A physical quantity, property, or condition that is measured.

Measurement: The process of quantitatively comparing a variable characteristic, property, or attribute of a substance, object, or system to some norm.

Measurement innovation: Technological innovation where the new technology is a measurement technology.

Measurement result: Quantitative result of the measurement process, achieved to a level of certainty influenced by a combination of technical and human elements that include measurement methods, instruments, information, standards, and institutions.

Measurement system: The entire set of technical and human elements involved in producing measurements for an intended purpose.

Metrology: The science of measurement.

MRA: Mutual Recognition Arrangement.

N

NCWM: National Conference on Weights and Measures, a private, nonprofit organization with representatives from industry, states, and the federal government that develops standards, test procedures, and model laws and regulations on weights and measures.

NIST: National Institute of Standards and Technology; an agency in the U.S. Department of Commerce, responsible for maintaining U.S. national standards of measurement.

NMI: National Measurement Institute.

NMS: National Measurement System.

O

OIML: International Organization of Legal Metrology, which develops model international standards of measurements used for regulatory purposes, such as commodity exchange and environmental monitoring.

OSTP: Office of Science and Technology Policy, an office within the Executive Office of the President of the United States, with a broad mandate to advise the President and others on the effects of science and technology on domestic and international affairs.

Other observations: The term used in this report to indicate a declarative statement from the inferential analysis about a potentially significant measurement issue that has been reviewed by industry representatives but does not meet the standard of a finding.

P

Public sector: The part of the economy concerned with providing basic government services.

Private sector: The part of the economy made up of private firms and companies, corporations, private banks, non-governmental organizations, and individuals.

R

RFID: Radio frequency identification.

RMO: Regional Metrology Organization.

R&D: Research and development.

Roadmap Measurement Needs: Summaries of industry measurement needs abstracted from published technology roadmaps.

S

Sector/Technology areas: A term used in this report to represent an industrial sector and/or technology area.

SDO: Standards-Developing Organization.

SI: International System of Units (abbreviated SI from the French language name Système International d'Unités), which is the modern form of the metric system. It is the world's most widely used system of units, both in everyday commerce and in science.

SIM: Inter-American Metrology System, an organization with the goal of promoting international and regional cooperation in the Americas for scientific, industrial, and legal metrology.

T

Technical barrier: A deficiency or absence of a technical capability that impedes technological innovation.

Technological innovation: Either a process or a physical entity; as a process, it is that part of the overall innovation process relating to the introduction into the marketplace of new technology; as a physical entity, it is the new technology itself.

Technology Developer's Vision: The conceptual view of what the new technology will functionally do, who the user of the new technology will be, and what benefit to the user that technology will yield.

Technology roadmap: Consensus document identifying targets of opportunity and barriers to envisioned technologies in a particular industry based on the views of representatives from industry, academia, and, often, government.

U

USMS: United States Measurement System, which includes the methods, standards, instruments, and private and public organizations involved in measurements of products and processes or in other measurement-related activities relevant to the functioning and performance of the national economy.

Endnotes

1 Council on Competitiveness, *Innovate America: Thriving in a World of Challenge and Change*, 2nd ed. (Washington, D.C.: 2004-5).

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3 Domestic Policy Council, Office of Science and Technology Policy, *American Competitiveness Initiative: Leading the World in Innovation* (Washington, D.C.: 2006).

4 Examples include:
- R.D. Huntoon, "Concept of a National Measurement System: The systems approach is being applied to improve understanding of the nation's measurement activities," *Science*, 158: 67-71, October 1967.
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- GM Peter Swann, "The Economics of Measurement," *Report for the United Kingdom National Measurement System Review*, June 1999.

These and related studies are summarized in:
- John Birch, *Benefit of Legal Metrology for the Economy and Society, A Study for the International Committee of Legal Metrology*, 2003.

5 The ITRS defines metrology as "the measurements made to research, develop, and manufacture integrated circuits, including measurements made on materials used for integrated circuits and their manufacturing."

6 *International Technology Roadmap for Semiconductors*, 2005 Edition: Metrology, 1.

7 Magnetic data storage was added after the assessment process began. Workshop and industry submissions yielded a large number of measurement needs in this advanced technology area, which is basic to progress in enhancing the capabilities of information and communication technology.

8 Several recent studies point to pending breakthrough technologies, including National Science and Technology Council, *National Nanotechnology Initiative—Research and Development Supporting the Next Industrial Revolution*, 2003; the President's Council of Advisors on Science and Technology (PCAST), *The National Nanotechnology Initiative at Five Years: Assessment and Recommendations of the National Nanotechnology Advisory Panel*, 2005; and the *International Technology Roadmap for Semiconductors*, 2005 Edition.

9 The importance of measuring system performance in service industries is indicated in the U.S. Department of Commerce, *Radio Frequency Identification: Opportunities and Challenges in Implementation*, 2005.

10 Several recent studies indicate the importance of measuring system performance in service industries, including the National Science and Technology Council, *Networking and Information Technology Research and Development—Advanced Foundations for American Innovation*, 2003; The President's Council of Advisors on Science and Technology, *Sustaining the Nation's Innovation Ecosystem: Maintaining the Strength of Our Science and Engineering Capabilities,* 2004; U.S. Department of Commerce, Office of Technology Policy, *Innovation, Demand and Investment in Telehealth*, 2004; and the U.S. Department of Commerce, *Radio Frequency Identification: Opportunities and Challenges in Implementation*, 2005.

11 The need for new measurement capabilities to enable sensing technology breakthroughs have been documented in a number of 2006 news stories in *Sensors* Magazine. Also, in two reports by the President's Council of Advisors on Science and Technology: *Report on Energy Efficiency*, 2003; and *The Science and Technology of Combating Terrorism*, 2003; in the National Academy of Engineering, *Frontiers of Engineering: Reports on Leading-Edge Engineering from the 2005 Symposium*; in U.S. Climate Change Technology Program, *Strategic Plan: Draft for Public Comment*, 2005; and in the National Science and Technology Council, *Grand Challenges for Disaster Reduction*, 2005.

12 Evidence that progress in measurement science leads to new understanding and new measurement capabilities can be found in three documents by the President's Council of Advisors on Science and Technology: *Sustaining the Nation's Innovation Ecosystems, Information Technology Manufacturing and Competitiveness* (2004); *Sustaining the Nation's Innovation Ecosystem, Maintaining the Strength of Our Science and Engineering Capabilities* (2004); and *Assessing the U.S. R&D Investment* (2002). Also, see National Academy of Sciences, *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future* (forthcoming 2006); Council on Competitiveness, National Innovation Initiative, *Innovate America: Thriving in a World of Challenge and Change*, 2nd ed. (2004-05); and in National Academy of Sciences, *Advanced Research Instrumentation and Facilities* (forthcoming 2006).

13 H. Arthur Klein, *The Science of Measurement: a Historical Survey* (Dover Publications, 1988).

14 National Academy of Sciences, *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future* (Washington, D.C.: The National Academies Press, Forthcoming 2006).

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Appendices
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